CRASH RISK MODELS FOR MOTORCYCLE-DOMINATED TRAFFIC ENVIRONMENT OF URBAN ROADS IN DEVELOPING COUNTRIES

by

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ABSTRACT

Road safety is a global issue. Road crashes are estimated to be the eighth leading cause of death and result in approximately 1.25 million deaths and 50 million nonfatal injuries on the world's roads every year. The crash statistics show that 50% of the world's road crash deaths occur among vulnerable road users (e.g. pedestrians, cyclists, motorcyclists) and among them, motorcyclist deaths account for 23%. In a number of developing countries, motorcycles are the predominant vehicle type because of their affordability and ease of use particularly in urban environments. Consequently, the number of crashes resulting in death and serious injury involving motorcycles in these countries is significant. Particularly in most Southeast Asian countries, motorcycle crashes may reach about 70% of the total road crashes.

In motorcycle-dominated traffic environments, motorcycles do not usually conform to lane disciplines as passenger cars do and they tend to swerve to change their directions and speeds frequently. These movement characteristics are described as non-lane-based movements of motorcycles and were found to be major causes contributing to increased crash risk for motorcyclists. Although the non-lane-based movements of motorcycles have been found to be a significant risk factor contributing to motorcycle crashes, it seems that to date there are no models taking into account explicitly this risk factor. To this end, and to examine the effect of such manoeuvre of motorcyclists on crash risk, this research developed a methodology and associated models to estimate the potential of rear-end and sideswipe crashes.

The proposed methodology sought to provide a good estimate of both the rear-end crash and sideswipe crash risks for motorcyclists and the operating speed, the speed difference, the

traffic density, the front distance, the longitudinal gap, the lateral clearance and the road surface condition were found to contribute to these crashes risk.

In addition, a new concept of the Conflict Modification Factor (CoMF) was proposed as a measure to assess the crash risk for a particular road site and facilitate the development of an appropriate countermeasures programme by assessing the crash risk reduction effectiveness of a specific countermeasure. By using the developed crash risk models together with the proposed CoMFs, several potential countermeasures to improve motorcyclist road safety were identified. These were: i) installing changeable speed limit signs, ii) installing changeable gap warning signs, iii) installing changeable road surface condition warning signs and iv) providing segregated motorcycle lanes.

Furthermore, a methodology was also proposed to integrate the risk of rear-end and sideswipe crashes into the current International Road Safety Programme (iRAP) star rating system for motorcyclists and the proposed methodology seems to produce results consistent with historical crash data and subject to more testing, may be considered for full implementation.

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TABLE OF CONTENTS

CHAPTER 7

CHAPTER 8

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

AADT	Average Annual Daily Traffic
AASHTO	American Association of State Highway and Transport Official
CMF	Crash Modification Factor
CoMF	Conflict Modification Factor
DoT	Danang Department of Transport
FHWA	Federal Highway Administration
HIC	High-Income Countries
HSM	Highway Safety Manual
IATSS	International Association of Traffic and Safety Sciences
ITE	Institute of Transportation Engineers
iRAP	International Road Assessment Programme
ITS	Intelligent Transport Systems
KSI	Killed and Serious Injuries
LIC	Low-Income Countries
LMIC	Low- and Middle-Income Countries
MAG	Motorcycle Action Group
MIC	Middle-Income Countries
MIROS	Malaysian Institute of Road Safety Research
NHTSA	National Highway Traffic Safety Administration
NPRA	Norwegian Public Roads Administration
OEDC	Organization for Economic Cooperation and Development
SPF	Safety Performance Function

SSAM	Surrogate Safety Assessment Model
SRS	Star Rating Score
TSD	Threshold-Safety-Distance
VMS	Variable Message Signs
WHO	World Health Organization

NOTATIONS

a	maximum braking deceleration of motorcycles
D_{TSD}^{FM}	threshold-safety-distance for following manoeuvre scenario
D_{TSD}^{SM}	threshold-safety-distance for swerving manoeuvre scenario
d	stopping distance
e	base of the natural logarithm
$g(x)$	logit of the logistic regression model
La_{n-1}	lateral clearance of front vehicle
La_n^m	lateral gap between motorcycle and laterally-following vehicle
$Lo_{\mathrm{n}}^{\mathrm{n-1}}$	front distance
Lo_n^m	longitudinal gap between motorcycle and laterally-following vehicle
$L(\beta)$	log-likelihood function
ln(y)	natural logarithm of variable y
Te_{n-1}	type of front vehicle
Te_m	type of laterally-following
V_n^m	relative speed between motorcycle and front vehicle
V_n^{n-1}	relative speed between motorcycle and front vehicle
v	speed of vehicle
α	swerving angle of motorcycles
β	coefficient of independent variables
π(x)	conditional probability that the outcome is presence
μ	mean of the lognormal distribution

σ	standard deviation of the lognormal distribution
τ	reaction time of motorcyclists
Φ	cumulative standard normal distribution

CHAPTER 1

INTRODUCTION

1.1. Global Road Safety

Road safety is a global issue as road crashes are estimated to be the eighth leading cause of death and result in approximate 1.25 million deaths and 50 million nonfatal injuries on the world's roads every year (WHO, 2015). Road crash injuries have been increasing, particularly in low-income and middle-income countries, where rates are twice as high as those in high-income countries. In addition, as presented in WHO (2015), the road crash fatality rate is the highest in low-income countries (LIC), at 24.1 per 100,000 population, followed by middle-income countries (MIC) with a rate of 18.4 compared to only 9.2 in high-income countries (HIC). The report also indicates that 80% of road traffic deaths occurred in low- and middle-income countries (LMICs) while these countries account for only 54% of the world's registered vehicles.

Moreover, the crash statistics show that nearly 50% of the world's road crash deaths occur among vulnerable road users (e.g. pedestrians, cyclists, motorcyclists) and among them, motorcyclist deaths account for 23% (WHO, 2015). However, the proportion of crash deaths involving motorcyclists is different between regions. In most LMICs, motorcycles are used frequently because they are relatively affordable to buy and run. Consequently, road crash deaths among motorcyclists are very high in these countries. For example, in the South-East Asia region, the proportion of motorcycle crash deaths accounts for 34% of all crash deaths (see Figure 1.1).

This indicates that improving motorcyclist safety is a key road safety area requiring immediate action in both developed and developing countries. WHO (2013) has consequently defined it as a priority goal within the Decade of Action for Road Safety Global Plan (2011-2020).

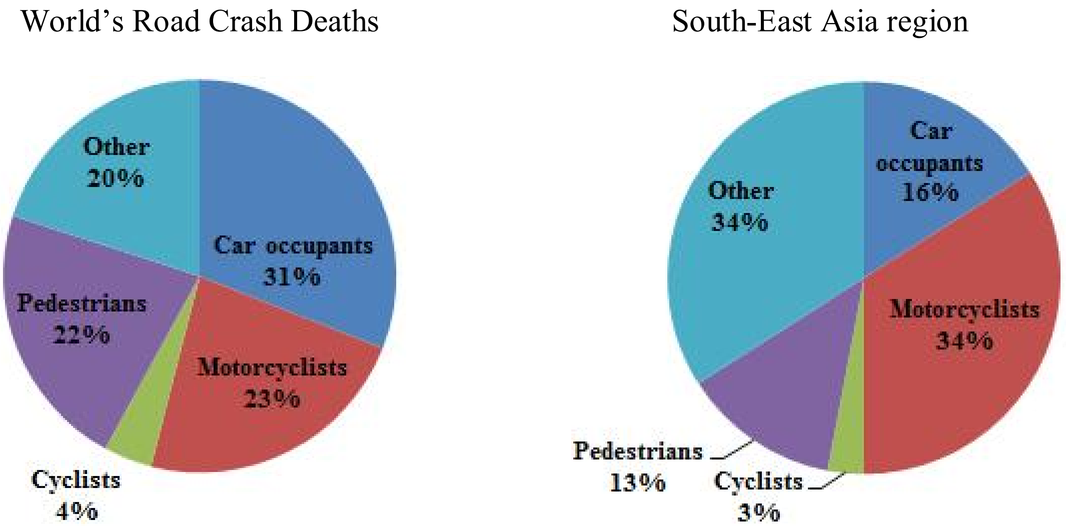


Figure 1.1. Road crash deaths by type of road user (WHO, 2015)

Motorcyclists’ safety is a major concern in a number of cities worldwide including most Southeast Asian cities where motorcycles are the predominant mode of transport. In recent years, although the number of passenger cars is increasing due to economic growth, motorcycling is still the predominant mode of urban transport in a number of LMICs worldwide, particularly in most Southeast Asian cities due to affordability and flexibility in terms of movement and parking. Consequently, the number of crashes resulting in death and serious injury involving motorcycles in these countries is significant. According to the report of WHO (2015), the number of motorcycles accounts for 54.1% of the total registered vehicles in the Southeast Asian countries, and the proportion of crashes involving motorcycles accounts for 34% of the total road crashes in this region. However, in certain countries, motorcycles' crashes may reach about 70% of the total road crashes (Manan and Várhelyi, 2012). For example, in the city of Danang in Vietnam, motorcycles constitute over 80% of total traffic, and motorcycle crashes account for nearly 70% of the total road crashes (DoT, 2013). Similarly, in Indonesia, it has been reported that motorcycles account for 78.3% of the total vehicle population and 75% of fatalities in traffic crashes involved motorcyclists (Indriastuti and Sulistio, 2010). This issue has also been reported in Taiwan (Ming, Wucheng and Cheng, 2013) and Malaysia (MIROS, 2011).

As motorcycling is the predominant mode of transport and motorcyclists are involved in a large proportion of road crashes, motorcyclist safety is a crucial issue in the Southeast Asian region. A crash results from a number of risk factors related to humans, vehicles and environment, and the effect of these risk factors on crash potential is different between areas, countries and regions (Elvik *et al.,* 2009; WHO, 2015). Therefore, to improve motorcyclist safety in the environment of LMICs and particularly in Southeast Asia countries, it is necessary to identify the major causes and associated risk factors leading to motorcycle crashes in this particular traffic environment.

1.2. Road Safety in Vietnam

Road safety is a major concern in Vietnam as road crashes result in about 11,000 deaths every year and economic losses are estimated to account for approximately 2.89% of the national annual gross domestic product. This issue is particularly urgent for motorcyclist safety as motorcycle is the predominant mode of transport in Vietnam, accounting for about 87.5 % of total registered vehicles, and the number of new registered motorcycles has been increasing every year (NTSC, 2014). In 2013 for example, the data shows that there was

11,785 road crashes occurring and resulting in 11,094 deaths and 7,559 injuries. The crash statistics indicate that motorcycle crashes account for 81.2% of total road crashes and 75.8% of fatal crashes involved motorcyclists (see Figure 1.2). As also revealed from the crash data, the percentage of crashes occurs on national highways, urban and rural roads were 27.9%, 46.9% and 25.2% respectively (NTSC, 2014).

This situation suggests that there is a need of urgent actions to improve urban traffic safety in general and motorcyclist safety in particular in Vietnam.

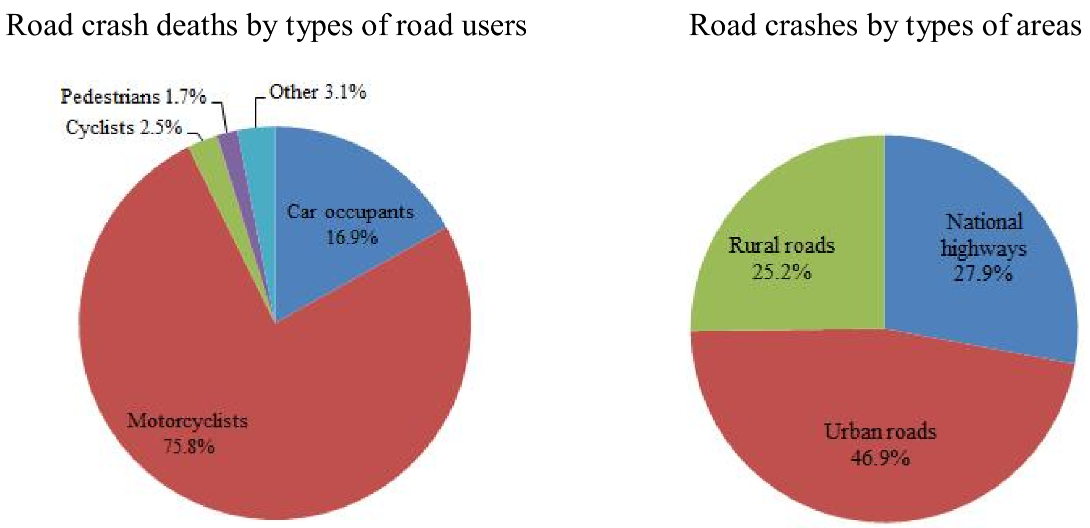


Figure 1.2. Road crash statistics in Vietnam in 2013 (NTSC, 2014)

1.3. Problem Definition

In motorcycle-dominated traffic environments, motorcycles do not conform to lane discipline and lane markings as passenger cars do, and they tend to swerve to change their direction and speed frequently (Hsu, Sadullah and Dao, 2003; Minh, 2007; Huyen, 2009; Long, 2012; Shiomi *et al.,* 2013). These movement characteristics are described as 'non-lane-based movements' and were found to be major causes (or risk factors) contributing to crash potential (Indriastuti and Sulistio, 2010; Long, 2012; Ming, Wucheng and Cheng., 2013).

According to Hosking, Liu and Bayly (2010), and Wong, Chung and Huang (2010), the movement behaviour of motorcyclists is one of the most important human factors in road safety, especially in developing countries. In Vietnam for example, crash data revealed that "failed to keep safe following gap", "changing lanes improperly", and "failed to look properly" are three most common causes of motorcycle-involved crashes, accounting for 19.3%, 16% and 15.9% respectively (DoT, 2013). These risky movement behaviour of motorcyclists have resulted in a large proportion of rear-end and sideswipe crashes involving motorcycles. For example in Danang, the crash statistics show that rear-end and sideswipe crashes account for 25.9% and 36.3% of the total motorcycle crashes in urban environment respectively (DoT, 2013). Similarly, in Taiwan, it has been reported that rear-end and sideswipe crashes account for 20% and 32% of the total motorcycle-involved crashes on urban roads (Ming, Wucheng and Cheng, 2013). This issue has also be reported in Indonesia and Malaysia (Indriastuti and Sulistio, 2010; Manan and Várhelyi, 2012).

Although the non-lane-based movement characteristics of motorcycles have been found to be a significant factor contributing to motorcycle crashes, it seems that to date there are no models that take into account explicitly these risk factors. To this end, and to examine the effect of such manoeuvre behaviours of motorcyclists on crash risk, this study developed a methodology and associated models to estimate the potential of rear-end and sideswipe crashes associated with these manoeuvre characteristics for motorcycles moving in a motorcycle-dominated traffic environment of urban roads. The preliminary results of the proposed models may be used to support traffic engineers in improving urban road safety and developing appropriate countermeasures to mitigate the crash risk for motorcyclists. Furthermore, the proposed methodology is expected to provide a better understanding of the influence of non-lane-based movement characteristic of motorcycles on crash potentials, and to trigger further research on road safety assessment for motorcyclists in LMICs where motorcycles are the predominant mode of urban transport.

1.4. Aim and Objectives

The aim of this project was to enhance motorcyclist safety and offer practicable countermeasures by examining the movement characteristics of motorcycles in a motorcycle-dominated traffic environment of urban roads, such as those found in Southeast Asian countries and using the city of Danang in Vietnam as a typical road environment.

The specific objectives were:

1. To develop crash risk models to estimate the potential of rear-end and sideswipe crashes for motorcycles in a motorcycle-dominated traffic environment of urban roads.
2. To investigate the effect of contributing factors on motorcycle crash potentials and to assess the relative contributions of these risk factors to rear-end and sideswipe crashes for motorcyclists.
3. To develop a new measure to assess the motorcyclists crash risk without reliance on historical crash data.
4. To identify countermeasures related to the specific risk factors of motorcyclist safety for implementation in urban areas of LMICs.

5. To develop a methodology to enhance the existing International Road Assessment Programme (iRAP) star rating system for motorcyclists based on the crash risk models developed in this study.

1.5. Thesis Layout

To meet the above aim and objectives, this thesis is structured as follows:

Chapter 2 gives the literature review for this research. It includes the review of two main modelling approaches in road safety analysis, existing road safety assessment tools, the unique characteristics of motorcycles and their crash risk factors, and also existing studies related to motorcyclist safety, risk factors contributing to motorcycle crash risk and associated countermeasures.

Chapter 3 presents the methodology of this research. It includes its overall approach, the modelling approach adopted and the statistical techniques used to develop crash risk models. It outlines the approach used to determine the contributing risk factors included in the models, and the approach followed to identify countermeasures related to these specific risk factors.

Chapter 4 describes the process of developing both rear-end and sideswipe crash risk models. In this chapter, the model forms are presented along with a detailed description of the steps used to build these two models.

Chapter 5 shows the methodology used to collect the data for model fitting and model validation. A summary of the characteristics of the road segments datasets are also presented.

Chapter 6 presents the process of fitting the models. In this chapter, the coefficients of variables are estimated based on real traffic data. The significance of variables is also assessed with the view to determine whether the variables included in the model are significantly related to the outcome variable and the insignificant variables are removed from the model to achieve the best fitting model.

Chapter 7 shows the process of validating the models. In this chapter, three validation tasks are conducted to assess the performance of the developed models including: (1) assessing the goodness-of-fit to test how effective the model is in describing the outcome variable, (2) field validation to compare the output from the developed models with the real data collected in the field, and (3) a test to compare the output from the developed models with that from the existing models found in the literature and with actual historical crash data.

Chapter 8 presents the sensitivity analysis results of the developed models with regard to the effects of the variables included in the risk models of the rear-end and sideswipe crashes.

Chapter 9 shows the process of developing the new concept of the Conflict Modification Factor (CoMF) together with an examination of the relative contributions of factors to the overall crash risk.

Chapter 10 describes the methodology being suggested to enhance the existing the iRAP star rating system for motorcyclists.

Chapter 11 gives the discussion of this research.

Chapter 12 presents the conclusions and future work.

CHAPTER 2

LITERATURE REVIEW

This chapter presents the literature review on road safety assessment models, risk factors and countermeasures and it is organised as follows. The first section reviews two main approaches applied in road safety analysis. The second section summarises the methodologies of two existing road safety assessment tools. The third section reviews the unique characteristics of motorcycles that affect crash potential and then, motorcycle movement behaviour models are summarised in section four. The fifth section reviews studies related to motorcyclist safety for both motorcycle-dominated traffic environments and conventional traffic environments. The next section reviews risk factors contributing to motorcyclist safety and then countermeasures are summarised in the final section.

2.1. Road Safety Assessment Approaches

There are two main approaches in road safety assessment: the traditional approach which is based on historical crash data and the surrogate approach which is based on the observation of traffic conflict events (Saunier, 2013).

2.1.1 Traditional road safety assessment approach

2.1.1.1 Modelling method

Road safety is associated with crash risk. To assess the crash risk, most traditional road safety approaches have been based on historical crash data to build safety performance functions (or crash prediction models) via a regression equation using various statistical analyses to estimate the expected number of crashes for a particular road location (Archer, 2004; Gettman, *et al.,* 2008; HSM, 2009). A safety performance function (SPF) is a mathematical function used to describe the relationships between road crash frequencies and traffic volume, road geometric features, and traffic control features. The basic form of a SPS is as follows (Reurings *et al.,* 2005):

$$N = \alpha V^{\beta} e^{\sum \gamma_i x_i}$$

(Equation 2.1)

where, N is the estimated number of crashes, V is the traffic volume, x_i (i = 1, 2, 3 … n) is a set of risk factors, α, β and γ are estimated coefficients.

For example, Bonneson and McCoy (1997) predicted the number of crashes on urban road segments as a function of explanatory variables including the average annual daily traffic, the median treatment type, the section length, the land use, the parallel parking, the driveway density, and the public street approach density. The historical crash data used to develop the model were collected in the city of Phoenix in Arizona and the city of Omaha in Nebraska over three years from 1991 to 1993. Qudais (2001) developed crash prediction models for urban roads in the city of Irbid in Jordan. The models were built based on observed crash data collected over three years from 1996 to 1998. They found that the lane width is the most significant factor contributing to the number of crashes per million vehicle kilometres. Moreover, the number of lanes, the average annual daily traffic, the road surface condition, the peak hour factor and the speed factor were found to influence the estimated number of crashes. Greibe (2003) built crash prediction models to predict the expected number of crashes on road sections in urban areas in Denmark by using data collected from 142 km urban roads and historical crash data collected over five years from 1990 to 1994. They found that the number of crashes per year per km was significantly affected by contributing factors such as the average annual daily traffic flow, the speed limit, the road width, the parking facilities and the land use.

2.1.1.2 Limitations of the traditional approach

It seems that the traditional road safety approach has received considerable attention and a large number of safety performance functions (crash prediction models) have been developed in a number of countries (Mountain and Fawaz, 1996; Sayed and Rodriguez, 1999; Lord and Persaud, 2000; Bauer and Harwood, 2002; Greibe, 2003; Salifu, 2004). Such models focused on establishing the relationship between the number of crashes or crash rate and risk factors by using various statistical regression methods. However, key drawbacks of this approach are that the driving behaviour of road users was not considered and there is a problem in obtaining a reliable historical crash data for the model development process particularly in countries where crash data were not recorded sufficiently. The use of historical crash data in road safety analysis is likely to produce unreliable estimates of crash frequency and severity as well as an increase in the level of uncertainty of the estimated influences of road safety treatment measures due to the following reasons:

- Crashes are rare events and therefore it takes a long time period to obtain a sufficient amount of crash data for model development. For example, to build crash prediction models, the historical crash data used in the modelling process are required to observe at least over 3-5 years, in order to satisfactorily capture the effect of risk factors on crash occurrences. If longer time periods are analysed, risk factors such as traffic volume, weather, traffic control, land use and geometric design may change over time, and therefore it is difficult to associate their changes to the crash frequency during the study periods (HSM, 2009; Laureshyn, 2010).

- Crashes are random events and therefore the number of crashes observed at a particular location is likely to fluctuate over time. For this reason, the use of short-term crash frequencies alone is not reliable to estimate the frequency of crash occurrence in the long term. In addition, this characteristic causes difficulty in determining whether the change of crash frequency is caused by the effectiveness of a treatment at that location or by its fluctuation characteristic (HSM, 2009; Laureshyn, 2010).

- Not all crashes are recorded. In addition, the level of under-reporting and accuracy depends on the crash severity and road user types. It was found that fatal and severe injury crashes are reported more reliably than property-damage-only and slightly injurious crashes. This may produce biassed estimates if the issue of underreporting is not considered in the modelling process (HSM, 2009; Ismail, 2010; Laureshyn, 2010).

- The information related to the mechanism of crash occurrence is not normally fully recorded in crash reports (e.g. road users behaviour leading to crashes). Without understanding the failure mechanism and the contribution of risk factors on crashes, it is difficult to identify appropriate countermeasures to prevent the occurrence of crashes (HSM, 2009; Ismail, 2010; Laureshyn, 2010).

Due to the aforementioned limitations of using historical crash data for model development, there is a growing interest in using surrogate safety measures for road safety assessment (Gettman and Head, 2003). Surrogate in this context means that these measures are not based on observed crash data, but rather on other occurrences of traffic events that are causally related to the process of crashes occurring (Laureshyn, 2010).

2.1.2 Surrogate safety measures approach

As discussed in the previous section, to overcome the limitations of traditional road safety analysis, surrogate safety measures have been proposed and used in road safety assessment. The most commonly used surrogate safety measure is related to the traffic conflict techniques (Gettman *et al.*, 2008; Guo *et al.*, 2010).

The traffic conflict technique is an approach to estimate traffic safety aspects based on observing and recording traffic events that are not as severe as crashes, but similar to them in terms of the mechanisms (Hydén, 1987). This technique is based on the observation of interactions between road users to estimate the potential of crashes and it has been advocated as an alternative approach to crash-based road safety analysis (Ismail, 2010).

The traffic conflict technique was initially presented in 1968 by Perkins and Harris at the Detroit General Motors Laboratory in USA (Perkins and Harris, 1968). Thereafter the use of traffic conflict technique in road safety assessment has been spread to a number of countries. Miglez, Glauz and Bauer (1985) established the relationship between traffic conflicts and crashes using data collected at 46 signalised and un-signalised intersections in the Greater Kansas City area. They found that the estimates of average crash frequencies based on traffic conflicts were nearly accurate as the observed crash data. Hydén (1987) proposed a general model to describe the relationship between normal traffic events, traffic conflicts and crashes which can be visualised as a pyramid shown in Figure 2.1. The top of the pyramid represents the occurrence of crashes due to the failures of taking evasive actions of road users involved in the most severe conflicts. Traffic conflict events (or near-crashes) are located next to the crash events and they are classified as serious, slight or potential conflicts based on the level of their severities. Potential conflicts refer to events where two road users approach each other and the occurrence of a conflict is imminent unless at least one road user takes an evasive action. Slight conflicts refer to events that two road users approach each other and the potential of a serious conflict is obvious. Serious conflicts refer to events that two road users are in a situation that they must take a sudden and harsh actions to avoid crashes. Serious conflicts will lead to crashes if road users involved in conflict events cannot take evasive action sufficiently. The outcome of a serious conflict therefore may be a near-crash or crash. Below the conflict events of this pyramid are the normal traffic events that will not lead to conflict potentials between vehicles.

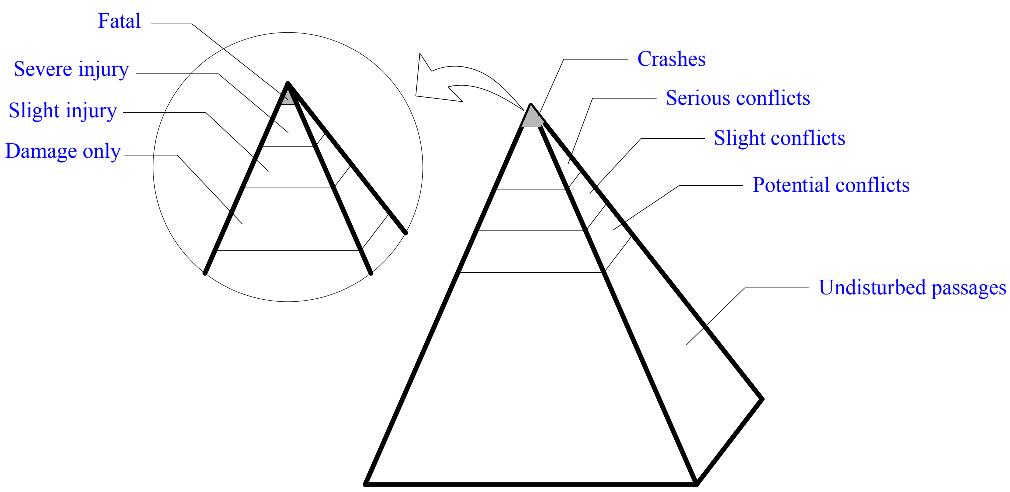


Figure 2.1. The pyramid model (Hydén, 1987)

Similarly, HSM (2009) described the continuum of traffic events that may lead to crashes and the proportion of crash events to non-crash events as shown in Figure 2.2. According to this relationship, the occurrence of crashes resulting from serious conflict events in which road users failed to take evasive action properly to avoid crashes.

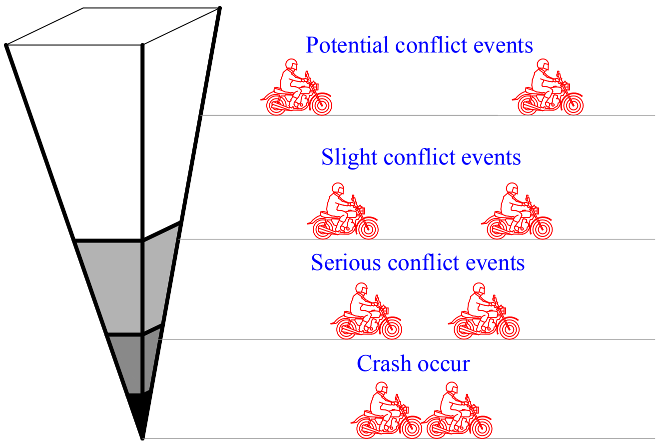


Figure 2.2. The relationship between conflict and crash events (HSM, 2009)

Gettman *et al.* (2008) developed a Surrogate Safety Assessment Model (SSAM) to determine the occurrence of traffic conflicts for a specific site. The SSAM tool is available to the public from the Federal Highway Administration (FHWA). The surrogate measures developed in SSAM are based on the identification, classification, and evaluation of traffic conflicts that occur in the simulation model. The model was validated by comparing the outputs from the SSAM with real-world crash records at eighty-three intersections from British Columbia, Canada. They found that the simulation-based intersection conflicts data provided by SSAM were significantly correlated with the crash data collected in the field.

Guo *et al.* (2010) conducted a 100-car naturalistic driving study to evaluate the relationship between near-crash (conflict) and crash events and the use of near-crash as a surrogate measure to crash analysis approach in crash risk assessment. They investigated the effect of contributing factors (e.g. gender, age group, level service, lighting conditions, traffic density, road alignment, road surface condition and weather) on both crash and near-crash events and they found that there is a strong relationship between crashes and near-crashes frequency. In addition, they also found the influence of risk factors on the causal mechanism of crashes and near-crashes is not significantly different and the use of near-crashes as surrogates can significantly improve the precision of the estimation. From the findings of their research, they suggested that the use of near-crashes as surrogate measure is informative for crash risk assessment and will help identify contributing factors that have a significant impact on crash risk for small-scale studies with the limited number of observed crashes.

2.2. Road Safety Assessment Tools

2.2.1 Highway Safety Manual (HSM)

The Highway Safety Manual (HSM) was published in 2009 by the American Association of State Highway and Transport Official (AASHTO) to assist users in developing road safety management programmes. The HSM provides tools for identifying locations with the most potential of crash frequency and severity, identifying risk factors contributing to crashes and potential countermeasures to improve road safety, and then evaluating the crash reduction effectiveness of selected countermeasures. To determine locations needed for safety treatments, the HSM developed a predictive method to estimate the expected average crash frequency for a network, facility or individual location. Each predictive model in the HSM methodology consists of a Safety Performance Function (SPF), which is adjusted to site specific conditions using Crash Modification Factors (CMFs) and to local jurisdiction conditions using a calibration factor (C). The general form to estimate the average crash frequency for a particular site (x) is as follows:

$$N_{predicted} = N_{spfx} \times (CMF_{1x} \times CMF_{2x} \times \ldots \times CMF_{ix}) \times C_x$$

(Equation 2.2)

where, $N_{predicted}$ is the predicted average crash frequency for a specific year for site type x, N_{spfx} is the predicted average crash frequency determined for base conditions of the SPF developed for site type x, CMF_{ix} is the Crash Modification Factor specific to SPF for site type x, C_x is the calibration factor to adjust for local conditions for site type x.

The SPF is an equation that estimates the average crash frequency for a site with the base conditions (e.g. a specific set of geometric design and traffic control features). SPFs were modelled as a function of traffic volume and roadway characteristics (e.g. number of lanes, median type, intersection control, number of approach legs) based on observed crash data using statistical regression techniques. In the HSM methodology, SPFs were developed for segments and intersections for urban and suburban arterials, rural multilane highways and rural two-lane roads. For example, the SPF for four-lane divided arterials is as follows:

$$N_{spf} = \exp(-12.34 + 1.36 \times \ln(AADT) + \ln(L))$$

(Equation 2.3)

where, N_{spf} is the predicted average annual multiple-vehicle crashes, AADT is the average daily traffic volume (vehicles/day) on roadway segment, L is the length of roadway segment (mi).

In the HSM methodology, a Crash Modification Factor (CMF) is a factor that estimates the changes in crash frequency or crash severity due to the implementation of a particular countermeasure.

2.2.2 The International Road Assessment Programme (iRAP)

The International Road Assessment Programme (iRAP) is a registered charity and a member of the United Nations Road Safety Collaboration that was established to support in tackling the devastating social and economic cost of road crashes with the view to meet the needs and data availability of low- and middle income countries. iRAP has developed a methodology to assess and improve the safety of roads by inspecting high-risk roads, developing Star Ratings, building Crash Risk Maps and Safer Roads Investment Plans. Star Ratings are developed to assess the safety level for a particular road segment, ranging from 1-star to 5-star. The safest roads are 4-star and 5-star and the least safe roads are 1-star and 2-star. Star Rating Scores for specific road segments are determined based on an assessment of infrastructure attributes and are linked to the likelihood and severity of crashes.

Four Star Rating Score (SRS) are produced separately for four road user types including vehicle occupants, motorcyclists, bicyclists and pedestrians. The SRS methodology was developed based on the types of crashes that account for a large proportion of road deaths and serious injuries for each road user as shown in Table 2.1.

Table 2.1. Crash types included in the SRS methodology (iRAP methodology, 2013)

Vehicle occupants	Motorcyclists	Bicyclists	Pedestrians
• Run-off road • Head-on • Intersections • Access points	• Run-off road • Head-on • Intersections • Access points • Moving along the road	• Travelling along road • Intersections • Run-off road	• Walking along road • Crossing road

The SRS is calculated for each 100 metre segment of road and each of the four road users by using the following equation (iRAP methodology, 2013):

$$\text{SRS} = \Sigma \text{ Crash Type Scores}$$

(Equation 2.4)

where,

- The SRS represents the relative risk of death and serious injury for an individual road user
- Crash Type Scores = Likelihood × Severity × Operating speed × External flow influence × Median traversability

(Equation 2.5)

where,

- Likelihood refers to road attribute risk factors that account for the chance that a crash will be initiated;
- Severity refers to road attribute risk factors that account for the severity of a crash;

- Operating speed refers to factors that account for the degree to which risk changes with speed;
- External flow influence factors account for the degree to which a person's risk of being involved in a crash is a function of another person's use of the road;
- Median traversability factors account for the potential that an errant vehicle will cross a median.

The iRAP methodology is particularly useful to road safety engineers as a proactive tool that can be used where road crash data are not readily available. However, it should not be viewed as a substitute for the collection and analysis of crash data. This tool presents several limitations: (i) the underlying models are based on research undertaken in HICs which has been adapted for use in LMICs, (ii) it focuses mainly on inter-urban roads and, (iii) and limited validation has been undertaken in the traffic environment of LMICs.

2.3. Unique Characteristics of Motorcycles Affecting Motorcyclist Safety

2.3.1 Non-lane-based movement characteristics

When moving in a traffic stream, motorcycles use non-lane-based movement characteristics which are distinct from the conventional movements of passenger cars. This may increase crash risk for motorcyclists (Hsu, Sadullah and Dao*,* 2003; Minh, 2007; Lee, 2007; Huyen, 2009; Long, 2012; Shiomi *et al*., 2013). These manoeuvre patterns has been discussed in a number of previous studies.

2.3.1.1 Alongside manoeuvre

Due to their small size (with the average width of 0.75 m which accounts for only 25 per cent of an average lane width of 3.0 m), motorcycles occupy a small space while moving on roads and they are therefore capable of travelling alongside other motorcycles in the same lane (Hsu, Sadullah and Dao, 2003; Minh, 2007; Lee, 2007; Long, 2012). According to Minh (2007), alongside manoeuvre is described as the pair-riding manoeuvre of motorcycles and it is commonly observable in a motorcycle-dominated traffic environment.

2.3.1.2 Oblique following manoeuver

Due to a flexible movement characteristic, motorcycles can follow the preceding vehicle at an oblique position (Lee, 2007; Long, 2012). According to Lee (2007), this manoeuvre behaviour helps motorcyclists to achieve a better front view and a better condition to overtake the preceding vehicles.

2.3.1.3. Filtering manoeuver

Due to a small size and a flexible turning radius, motorcycles can move freely in the traffic stream. A motorcycle filters when it moves through the lateral clearance between vehicles to achieve a desired speed and a better riding condition (Elliott, Baughan and Broughton, 2003; Minh, 2007; Lee, 2007; Long 2012). According to Minh (2007), this behaviour is similar to the zigzag movement of motorcycles and they are frequently observable in motorcycle-dominated traffic environments.

2.3.1.4. Swerving manoeuvre

Due to a small turning radius, motorcycles can make turns easily. In a swerving manoeuvre, the motorcycle changes its current direction to move to the left or right beside the front vehicle. This may be sometimes followed by an overtaking or filtering movement. Swerving is a typical behaviour that represents the non-lane-based movement characteristic of motorcycles and can be observed frequently in motorcycle-dominated traffic environments

(Minh, 2007; Lee, 2007; Long, 2012). This movement behaviour may result in a sideswipe crash with a laterally-following vehicle.

In addition to the aforementioned non-lane-based movement characteristics, in a motorcycle-dominated traffic situation, motorcycles tend to maintain a short headway with their front vehicles (Hsu, Sadullah and Dao, 2003; Lee, 2007; Minh, 2007; Long, 2012). This behaviour may lead to the potential of rear-end crashes.

2.3.2 Braking reaction time

Braking reaction time is defined as the interval from the instant that the driver recognises the existence of an obstacle ahead that necessitates braking to the instant that the driver actually applies the brakes (ASSHTO, 2004). According to Green (2000), when passenger car drivers are fully aware of the time and location of the brake signal, they can detect a signal and move their foot from the accelerator to the brake pedal in about 0.70 to 0.75 sec. However, in the same condition, Ecker *et al.* (2001) found that the mean of braking reaction times for motorcycle riders on the rear-wheel and front-wheel brakes were 0.463 and 0.423 sec, respectively. Similarly, Minh (2007) measured the reaction times of 100 motorcycle riders and found that the average reaction time was 0.52 sec. Davoodi *et al.* (2011) also measured brake reaction time for motorcycle riders and investigated the difference between the brake reaction time of older and younger riders. Their findings suggested that the mean and standard deviation of motorcycles braking were 0.44 and 0.11 sec, respectively. They also claimed that the age and gender of riders did not have a significant effect on their reaction times.

According to Davoodi *et al.* (2011), the mean braking reaction time of a motorcycle rider is lower than that of a passenger car driver in the same situation. This may be explained by the fact that passenger car drivers need more time to lift the foot off the accelerator pedal, move it laterally to the brake, and then depress the pedal, whereas motorcyclists can depress the brake pedal directly and instantly (Davoodi *et al.,* 2011).

2.3.3 Braking deceleration characteristic

2.3.3.1 For passenger cars

The design standard of highways and streets (AASHTO, 2004) recommended a value of 3.4 m/s^2 for deceleration to calculate the stopping sight distance for passenger cars. The Traffic Engineering Handbook (ITE, 2009) suggested that a value of 3.0 m/s^2 is a comfortable deceleration for most passenger car drivers. According to a study conducted by Fambro *et al.* (2000), most passenger car drivers are likely to apply a braking deceleration greater than 5.6 m/s^2 when confronted with an unexpected object in the roadway and approximately 90 % of all drivers tend to decelerate at rates greater than 3.4 m/s^2 when confronted with an expected object.

2.3.3.2 For motorcycles

Ecker *et al.* (2001) conducted a study to determine the maximum deceleration for motorcycles by testing Austrian motorcyclists covering the full range of age and riding experience. In their test, the braking deceleration was measured under dry road conditions for straight-path braking manoeuvres starting from approximately 60 km/h to a full stop. They found that the mean of distance-averaged deceleration is 6.19 m/s^2 with a standard deviation of 1.2 m/s^2. Winkelbauer and Vavryn (2004) examined the braking performance of 134 experienced motorcyclists and compared between the decelerations produced by using their own motorcycles and ABS-equipped motorcycles. The findings revealed that the mean value for braking deceleration of all test riders using their own motorcycles was 6.6 m/s^2 with a standard deviation of 1.4 m/s^2 while that of for using ABS-equipped motorcycles was 7.8 m/s^2 with a standard deviation of 1.1 m/s^2. Davoodi and Hamid (2013) carried out a study to measure the motorcyclists' braking distances and decelerations for both unexpected and expected objects situations associated with wet and dry pavement conditions. For the braking manoeuvres to an expected object, the mean and standard deviation of the deceleration values on the dry pavement were 4.59 m/s^2 and 1.04 m/s^2 respectively while those of on the wet pavement were 3.66 m/s^2 and 0.72 m/s^2 respectively. For the scenario when the riders confronted with the need to stop for an unexpected object in the roadway, the mean of deceleration was 6.02 m/s^2 with a standard deviation of 1.32 m/s^2.

The literature review seems to suggest that the average braking decelerations measured in stop emergency braking manoeuvre on dry pavements are quite similar and were greater than the average braking deceleration for passenger cars under similar conditions.

2.4. Behavioural Modelling for Motorcycles

To model the behaviour of motorcycles in motorcycle-dominated traffic environments, a number of models have been developed to date. Minh (2007) developed a lane selection, gap acceptance and adjacent gap acceleration model to describe zigzag manoeuvre of motorcycles. They introduced the concept of the "motorcycle dynamic lane" where motorcycles do not follow the lanes as passenger cars lane but move flexibly between other vehicles. In other words, the motorcycle dynamic lane is not stable as passenger car lane but flexible according to the subject motorcycle position. The width of this lane is defined as the comfort area around the subject motorcycle and may be determined based on the lateral distance between two motorcycles in a paired riding. Similarly, Lee (2007) developed a longitudinal headway, oblique and lateral headway, and path choice model to describe motorcycle behaviour based on the concept of the “dynamic virtual lane”. They assumed that motorcycles follow virtual lanes formed dynamically in relation to the surrounding vehicles but their models focused only on the preceding vehicle which was assumed to be a passenger car. It is felt, however, that this assumption seems to be appropriate for traffic dominated by passenger cars rather than for traffic where the motorcycle is the predominant mode of transport. Moreover, Long (2012) developed a motorcycle-following model to describe non-lane based movements of motorcycles in mixed traffic condition based on a social force model. Although the model primarily captures the behaviour of motorcycles, it is limited in terms of explanatory variables considered in the model.

2.5. Motorcyclist Safety Assessment Models

2.5.1 In motorcycle-dominated traffic environments

Several researchers have examined the risk factors affecting motorcycle crash frequency in the traffic environment of low-income and middle-income countries by developing crash prediction models based on historical data and statistical methods.

For example, Harnen *et al.* (2006) developed a model to predict motorcycle crashes at junctions on urban roads in Malaysia using the generalised linear modelling approach. They found that the flow of non-motorcycles on a major road, the approach speed of vehicles, the junction geometry, the junction control and the land use are significant factors contributing to the occurrence of motorcycle crashes at junctions. In their model, the number of motorcycle crashes per year is modelled as a function of contributing factors as follows:

$$\text{MCA} = 0.01109 \cdot QNM_m^{0.2685} \cdot QNM_n^{0.0515} \cdot QM_m^{0.1036} \cdot QM_n^{0.1263} \cdot \exp(0.01515\text{SPEED} - 0.1171LW_m - 0.0874LW_n - 0.01694LN_m + \beta_7\text{CTRL} - \beta_8\text{SHDW} + \beta_9\text{LU})$$

(Equation 2.6)

where, MCA is the estimated yearly number of motorcycle crashes; β_7 = 0.0 and 0.0315 for signalised and non-signalised (CTRL) respectively; β_8 = 0.0, 0.02174 and 0.02745 for shoulder width (SHDW) of 0.0 m, ≤ 1.0 m and < 1.0 m respectively; β_9 = 0.0 and 0.01873 for non-commercial and commercial area respectively; QNM_m, QNM_n are non-motorcycle volumes on major road and minor road respectively; QM_m, QM_n are motorcycle volumes on major road and minor road respectively; SPEED is the approach speed on major and minor roads; LW_m, LW_n are the average lane width on major road and minor road respectively; LN_m, is the number of lanes on major road.

Indriastuti and Sulistio (2010) developed a probability model to predict the motorcycle crash occurrence for the city of Malang in Indonesia using a logistic regression model. They found that male riders, an increase in motorcycle ownership, long travel distances and reduced riding knowledge have a significant influence on the occurrence of motorcycle crashes. The probability of motorcycle crashes is modelled as a function of explanatory variables contributing to the occurrence of crashes as follows:

$$P(mca) = \frac{1}{1 + e^{-(0.4 + 1.07x_{2.1} + 0.21x_6 - 0.7x_{10.1} + 0.15x_{12.1} + 0.74x_{12.2} + 0.91x_{12.3} + 0.58x_{12.4} + 0.87x_{12.5} + 0.31x_{14.1}}}$$

(Equation 2.7)

where, P(*mca*) is probability of a motorcycle rider involving in an crash; x_2 is the gender factor ($x_{2.1}$ = male); x_6 is the number of motorcycle owned; x_{10} is the travel purpose factor

($x_{10.1}$ = social); x_{12} is the distance factor ($x_{12.1}$ = < 1.0 km, $x_{12.2}$ = 1.0 – 5.0 km, $x_{12.3}$ = 6.0 – 10.0 km, $x_{12.4}$ = 11.0 – 15.0 km, $x_{12.5}$ = 16.0 – 20.0 km).

A crash is the result of a number of contributing factors and their effects on crashes may be different between areas (e.g. rural or urban environment) and countries. Hence, a model developed for a specific area or country may not be transferable to other locations without calibration and validation. In addition, the usefulness of such models depends on the availability and quality of the data used for their modelling, arguably they may be appropriate for research purposes and not be appropriate for the practicing transport engineer.

Manan, Thomas and Andras (2013) developed a safety performance function for fatal motorcycle crashes on Malaysian primary roads using the generalised linear modelling approach. They established a relationship between motorcyclist fatalities per kilometre and a set of factors contributing to fatal motorcycle crashes, and they suggested that increases in traffic flow and the number of access points per kilometre contribute to an increase in motorcycle crash fatalities. The form of model is as follows:

$$\text{MCFatal/km} = \exp(-4.891) \cdot \text{ADTMC}^{0.404} \cdot \text{Access-per-km}^{0.262}$$

(Equation 2.8)

where, MCFatal/km is the number of motorcycle crash fatalities per kilometre, Access-per-km is number of access points per kilometre; ADTMC is the average daily traffic of motorcycles.

Using mixed effects logistic regression, Manan (2014) examined the contributions of motorcyclist behaviour and road environment attributes to the occurrence of serious conflicts involving motorcycles entering primary roads from access points. They suggested that motorcyclist behaviour is the main factor in predicting conflict occurrence, but they also found that traffic volume and speed limit factors contribute significantly to the occurrence of motorcycle conflicts.

2.5.2 In conventional traffic environments

Although a number of researchers focused on investigating the effect of manoeuvre behaviour of motorcyclists on crash risk, they mainly focused on the conventional traffic environment of high-income countries where the passenger cars are the predominant vehicle type.

For example, Elliott, Baughan and Saxton (2007) developed a motorcycle rider behaviour questionnaire and used generalised linear modelling to investigate the effect of motorcyclist behaviour on crash risk in the UK. They found five types of motorcycle rider behaviour relating to crash risk (i.e. traffic errors, speed violations, stunts, safety equipment and control errors) and suggested that traffic errors are the main factors in predicting crash risk for motorcyclists. Savolainen and Mannering (2007) used a crash database from the state of Indiana to estimate the probability of motorcyclists' crash-injury severities based on the nested logit model and standard multinomial logit model. They found that poor visibility, unsafe speed, alcohol consumption, not wearing a helmet and an increasing motorcyclist age are significant factors contributing to the increase of crash-injury severity for motorcyclists. Pai and Saleh (2008) developed models to evaluate factors contributing to the severity of motorcyclist injuries in sideswipe collisions involving motorcycles at T-junctions in the UK and found that motorcyclist injuries were more severe when an overtaking motorcycle collides with a turning vehicle and such manoeuvres took place more frequently at unsignaled junctions than at signaled junctions. Haque, Hoong and Helai (2009) developed models to investigate the factors contributing to motorcyclist fault in motorcycle crashes by using binary logistic regression. They examined the effect of roadway characteristics, environmental factors, motorcycle descriptions and rider demographics on the fault of motorcyclists involved in crashes at three location types (intersections, expressways and non-intersections). They suggested that the likelihood of at-fault crashes on expressways increases with increased motorcycle speeds and at-fault crashes at non-intersections increase in wet road surface conditions. They also found the potential of not-at-fault crashes decrease with the presence of surveillance cameras at intersection. Shaheed, Gkritzab and Hans (2013) used motorcycle crash data of Iowa from 2001 to 2008 to investigate the effect of factors on the severity outcomes in collisions involving motorcycles based on the mixed logit model. They found that the roadway surface condition, clear vision, light conditions, speed limit, and helmet have a significant impact on severe injury outcomes.

2.6. Risk Factors Related To Motorcycle Crash Risk

2.6.1 Human factors related to motorcycle crash risk

The aim of studying driver behaviour is to reduce the probability and the consequences of crashes related to driver errors within the traffic systems by designing countermeasures to prevent these errors (HSM, 2009). Driver errors have been found to be significant contributing factors in most crashes and driving behaviour of road users was identified as the most important risk factor (Ulleberg and Rundmo, 2003; HSM, 2009). Treat *et al.* (1977) found that the human, the road environment, and vehicle failures are factors contributing to approximately 95.4%, 44.2%, and 14.8% of crashes respectively and they also found the majority of crash causation is due to a mismatch between the road environment and road users' behaviour as shown in Figure 2.3. Similarly, Sabey and Taylor (1980) found the human factors contributed to 95% of the crash causations. The same situation was also stated in the study conducted by Sanders and McCormick (1992).

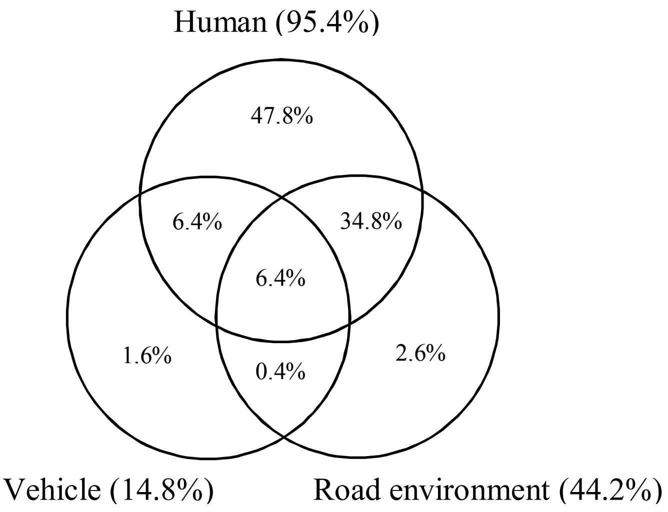


Figure 2.3. Proportion of crash causation factor (Treat *et al.,*1977)

2.6.1.1 Riding behaviour factor

Vlahogianni *et al.* (2012) stated that the common traffic violations related to the movement behaviour of motorcyclists were speeding, disobeying traffic signals, making illegal turns and maintaining short gaps with the preceding vehicles. Speeding was found to be the most frequent traffic violation of motorcyclists (Horswill and Helman, 2003; Elliott *et al.,* 2007). Shankar (2001) found that speeding contributed to about two-thirds of motorcyclist deaths in single vehicle crashes. Similarly, NHTSA (2007) stated that motorcyclist fatal crashes resulted from speeding causation were twice as high in comparison to other heavier vehicle types. Savolainen and Mannering (2007) found that speeding significantly increased the severity level of motorcycle crashes. According to Pai and Saleh (2007), the effect of speeding was more severe at un-signalised junctions. In motorcycle-dominated traffic environments, the unique movement characteristics of motorcycles such as swerving or weaving, filtering and maintaining short gap with preceding vehicles were found to be significant causes affecting motorcyclist safety (Hsu Sadullah and Dao*,* 2003; Minh, 2007; Lee, 2007; Huyen, 2009; Indriastuti and Sulistio, 2010; Long, 2012; Shiomi *et al.,* 2013; Ming, Wucheng and Cheng*,* 2013).

2.6.1.2 Operating speed factor

Elvik *et al.* (2009) found that high speeds and difference in speed between vehicles in the traffic flow are two significant factors contributing to the increase in the probability of crashes and serious injuries. They also found the risk of fatal injuries increases by the fourth power of the change in speed to which the body is exposed in a crash.

The higher the speed at the instant a crash occurs the more severe the crash consequence (Lin *et al.*, 2003; Lin and Kraus, 2009). Inappropriate speed for traffic conditions was found to increase crash risk (Claret, Ward and Truman, 2005). According to Aljanahi, Rhodes and Metcalfe (1999), the difference in speed between vehicles in a traffic stream has a significant contribution to the occurrence of crashes.

2.6.1.3 Age, gender and experience of motorcyclist factor

Riders characteristics such as age, gender and experience were found to have a significant influence on their movement behaviours. Young riders were found to have a stronger propensity for risky behaviours (e.g. speeding, aggressive behaviour, negligence of traffic regulations) and these risky movements have been shown to be associated with the increase in motorcycle crash risk (Sexton *et al.,* 2004; Yeh and Chang, 2009; Haque, Hoong and Helai, 2009). Older riders were found to be more involved in severe injury crashes due to the decrease in their physical resiliency and perceptual abilities (Savolainen and Mannering, 2007; Pai and Saleh, 2007; Nunn, 2011). Limited experience and poor driving skills were found to increase the occurrence of crashes (Claret, Ward and Truman, 2005; Chang and Yeh, 2007; Wong, Chung and Huang, 2010). According to Liu, Hosking and Lenne (2009), experienced motorcyclists were more likely to respond better to hazardous conditions compared to inexperienced motorcyclists.

2.6.2 Road environment factors related to motorcycle crash risk

2.6.2.1 Road geometry factor

Manan (2014) found the number of access points on roads had a significant effect on estimating the number of motorcyclist fatalities. They also found the road width and the presence of median contributed to the frequency of fatality crashes at access points. Similarly, Harnen *et al.* (2006) found the number of lanes, lane width and shoulder width have an influence on the number of motorcycle crashes at junctions. Motorcycle run-off crashes were found to occur more frequently at curve road segments (Sexton *et al.,* 2004; Clarke *et al.,* 2007). Schneider, Savolainen and Moore (2010) found the radius, the length and the shoulder width of curves are significant factors contributing to the frequency of motorcycle crashes on rural roads.

2.6.2.2 Road surface condition factor

Road surface conditions (e.g. surface grip, surface irregularities, potholes, loose materials and patch repairs) were found to account for about 15% of total motorcycle crashes (Haworth *et al.,* 1997). Shankar and Mannering (1996) stated that road surface conditions have a contribution to the occurrence of sideswipe crashes between motorcycles and other vehicles at junctions. According to Elliott, Baughan and Broughton (2003), wet bitumen surface caused steering problem for motorcyclists, particularly when they rode at high speed or applied a sudden brake. They also suggested that parallel longitudinal grooves in the road surface and inefficient road markings caused induce instability to motorcycle riders. Similarly, Haque, Hoong and Helai (2009) also found wet road surface was significant causation contributing to at-fault motorcycle crashes at non-intersections.

2.6.2.3 Roadside objects factor

Roadside objects were found to have a significant contribution to the severity of motorcycle run-off crashes (Vlahogianni, Yannis and Golias, 2012). Gabler (2007) found that the fatality rate of motorcyclists resulted from guardrail crashes accounted for 42% of all fatalities while crashing with concrete barrier accounted for 22% of fatalities. In addition, they also found the fatality rates of motorcyclists involved in guardrail crashes were approximately 80 times higher than that of for other drivers. Similarly, Daniello and Gabler (2011) found the fatal rates of motorcyclists were 7 times higher when crashing in guardrails compared with hitting the ground.

2.6.2.4 Visibility and lighting factor

Poor visibility was found to increase the severity level of motorcycle crashes (Savolainen and Mannering, 2007; Wanvik, 2009). NPRA (2004) found poor visibility increased the frequency of motorcycle crashes at intersections. Riding in darkness with no street lighting was also found to have an effect on the severity of motorcycle crashes (Lapparent, 2006; Pai and Saleh, 2008). Pai and Saleh (2007) found motorcycle crashes occurring after midnight were more severe, particularly at non-signalised intersections. Similarly, Haque, Hoong and Helai (2009) also found motorcyclists' injuries involved in crashes occurring during night time were more severe at both intersections and expressways.

2.6.3 Other factors related to motorcycle crash risk

2.6.3.1. Helmet use factor

Motorcyclists only rely on their own protection equipment if a crash occurs. The use of helmet while riding is a typical protection equipment for motorcyclists. It was found that the enforcement of helmet use significantly increases the motorcyclist safety (Morris, 2006; Houston, 2007; Mayrose, 2008). According to Houston (2007), after establishing the helmet use law in the USA, the proportion of fatalities related to severe head injuries reduced significantly.

2.6.3.2 Alcohol consumption factor

Alcohol consumption when riding was found to be a significant factor affecting the increase in motorcyclist crash risk (Huang and Preston, 2004; Kasantikul *et al.,* 2005; Lin and Kraus, 2009). Creaser *et al.* (2009) found that riding after consuming alcohol increased motorcyclist crash risk due to loss of attentiveness, slower reaction times, impaired judgment and poor performance on riding skills. Similarly, Haworth, Greig and Nielson (2009) also found alcohol consumption was associated with traffic violations such as speeding and non-use of helmets.

2.7. Countermeasures

There are a wide range of safety treatment measures that have been suggested and evaluated in a number of studies and tools. This study focused on reviewing several countermeasures that may have the potential to apply in urban areas to improve motorcyclist safety in the traffic environments of low-income and middle-income countries. The countermeasures were reviewed in this study presented in the Highway Safety Manual (ASSHTO, 2009), the iRAP toolkit (iRAP, 2013) and the Handbook of Road Safety Measure (Elvik *et al.,* 2009) related to road condition and traffic control measures such as providing separate motorcycle lanes, road surface condition improvement, speed limit, reduced-speed devices and traffic signs.

2.7.1 Providing segregated motorcycle lanes

The iRAP Toolkit (2015) suggested a countermeasure to reduce the potential for conflicts between motorcycles and larger vehicles in motorcycle-dominated traffic environments by providing segregated motorcycle lanes. As presented in the iRAP Toolkit (2015), motorcycle lanes can be inclusive or exclusive on the roadway. Inclusive motorcycle lanes are installed on the existing road and may be separated from the rest of the road by painted lines or physical barriers. Exclusive motorcycle lanes are constructed separately from that used by other vehicle types.

Providing separate motorcycle lanes in urban areas appears to reduce swerving or weaving manoeuvres by motorcyclists. They also separate motorcyclists from interaction with heavier vehicles. Therefore the frequency and severity of motorcycle crashes are reduced. The iRAP Toolkit (2015) suggested separate motorcycle lanes of at least 1.8 m wide for each direction and at least 3.6 m wide if overtaking is permitted. The effect of this countermeasure on motorcycle crashes is estimated within the iRAP tool as shown in Table 2.2.

Table 2.2. Estimated effect of segregated motorcycle lane on motorcycle crash (iRAP, 2013)

Facilities for Motorcycles	Likelihood of along crash type
Segregated one-way motorcycle path with barrier	0.0
Segregated one-way motorcycle path without barrier	0.1
Segregated two-way motorcycle path with barrier	0.0
Segregated two-way motorcycle path with barrier	0.1
Dedicated motorcyclist lane on roadway	1.0
None	2.0

Along crash type is defined as a crash occurs along the road between motorcycle and heavier vehicle

2.7.2 Road surface rehabilitation and resurfacing

Due to ageing, weathering and traffic activities, road surfaces may become worn or damaged. Therefore, road surface rehabilitation or resurfacing treatment is needed to improve the road surface to the required level of service. This treatment may provide a road surface with a high resistance to skidding and therefore reducing the potential of loss of control and rear-end crashes. As presented in the iRAP methodology (2013), the estimated effect of road surface condition on the likelihood of motorcycle crashes is shown in Table 2.3.

Table 2.3. Estimated effect of road condition on motorcycle crash (iRAP, 2013)

Road condition	Likelihood of motorcyclist crash	
	Run-off	Head-on (loss of control)
Good	1.0	1.0
Medium	1.25	1.25
Poor	1.5	1.5

2.7.3 Improving road surface friction

Friction affects both steering and braking distances and therefore good friction is an essential condition for vehicles to ride safely (Elvik *et al.,* 2009). Improving the friction of the road surface is to ensure a sufficient road grip for manoeuvring and braking during all weather and road surface conditions for normal traffic conditions. The friction of road surface can be improved by laying a new road surface with extra good friction (e.g. porous asphalt) on top of the old road surface (Elvik *et al.,* 2009). Improving friction has been found to have a significant effect on crash reduction. The relationships between friction and crashes have been investigated in a number of studies and were summarised by Elvik *et al.* (2009) as shown in

Table 2.4. The effects of friction improvement on crash reduction presented in this table were summarised from various previous studies conducted in different countries (e.g. UK and US). In addition, those studies focused on all crash types and all transport modes rather than focused on a particular crash type or motorcycle crashes only.

Table 2.4. Effects of friction improvement on crash reduction (Elvik *et al.,* 2009)

Measure	Types of crashes effected	Percentage of reduction
Increase of friction by 0.05, initial friction below 0.50	All crashes	10%
	Crashes on wet roads	35%
	Crashes on wet roads	1%
Increase of friction by 0.10, initial friction below 0.50	All crashes	17%
	Crashes on wet roads	42%
	Crashes on wet roads	10%
Increase of friction by 0.25, initial friction below 0.50	All crashes	32%
	Crashes on wet roads	56%
	Crashes on wet roads	12%

2.7.4 Road markings

Road markings have been applied to direct traffic by indicating the path of the carriageway and marking the road in relation to the surroundings, in order to help drivers to drive safety and comfortably. For example, the centre lines separate opposite traffic streams. Lane marking lines separate traffic lanes for traffic in the same direction. Edge lines mark the outer edge of the carriageway. Elvik *et al.* (2009) found that installing traffic lane lines and centre rumble strips reduced the number of all crashes to 18% and 4% respectively.

2.7.5 Speed limits

According to Elvik *et al.* (2009), a signposted speed limit states the highest permitted driving speed on a road and therefore the effects of changing speed limits on crashes, injuries and fatalities depend on the effects of the speed limit changes on the operating speeds. Elvik, Christensen and Amundsen (2004) summarised the relationship between speed limit changes and operating speed and they found when the speed limit is changed by 10 km/h, operating speed changes by about 2.5 km/h. They also suggested the relationship between changes in speed limit and changes in average operating speed may be described as a linear function as follows:

$$y = 0.2525x - 1.2204$$

(Equation 2.9)

where, y is the changes in average speed (km/h), x is the changes in speed limit (km/h).

Accordingly, they suggested the relationship between speed changes and changes in numbers of crashes, injuries and fatalities due to the changes of average operating speed may be described as a power function as follows:

$$\frac{Crashes\ after}{Crashes\ before} = \left(\frac{Average\ operating\ speed\ after}{Average\ operating\ speed\ before}\right)^{exponent}$$

(Equation 2.10)

where, exponent = 3.6 for all fatal crashes, exponent = 2.4 for all serious injury crashes, exponent = 1.2 for all slight injury crashes, exponent = 2.0 for all injury crashes and exponent = 1.0 for all property-damage-only crashes.

2.7.6 Speed-reducing devices

Speed-reducing devices have been applied to force vehicles to keep to low speeds, in order to reduce the risk of crashes. Several speed-reducing devices are commonly used such as speed humps and rumble strips (Elvik *et al*., 2009).

Speed humps are artificial elevations installed on the road to reduce the speeds of vehicles. Speed humps were found to reduce the operating speed and injury crashes to 24% and 41 % respectively (Elvik *et al.*, 2009). As presented in the HSM (2009), the installation of speed humps reduces the total number of crashes to 0.60 compared to the absence of this treatment.

Rumble strips are changes constructed in the road surface using coarse road surfaces or strips of plastic that lead to knocks, vibration or noise within the vehicles. Rumble strips were found to reduce the number of injury crashes at junctions by around 33% and the number of property-damage-only accidents by around 25% (Elvik *et al.*, 2009).

It is felt that these treatments seem to be appropriate for convention traffic environment rather than for motorcycle-dominated traffic environment as speed humps and transverse rumble strips can de-stabilise motorcycles.

2.7.7 Variable message signs

Variable message signs (VMS) are traffic signs on which a feedback or warning message can be displayed or altered as required. Variable warning signs may be used to warn road users of hazardous road surface condition, short headways between vehicles, or exceeding speed limit. For example, “advisory speed signs” are installed to warn drivers need to reduce their speeds. As presented in the HSM (2009), the provision of advisory speed signs reduces the total number of injury crashes to 0. 87 compared to the absence of signage.

Variable feedback signs may be used to inform information to road users about their behaviours in real time. These signs are commonly used to give feedback on compliance with speed limits and on too short headways between vehicles that may lead to the potentials of crashes. They are wired up to detectors and inductive loops installed in the road surface to record driver behaviour and to provide immediate feedback on it. For example, "changeable speed warning signs" give drivers feedback regarding their real-time speeds. As presented in the HSM (2009), the installation of changeable speed warning signs reduces the total number of injury crashes to 0.54 compared to the absence of signage.

As summarised by Elvik *et al.* (2009), the effect of different traffic signs on the reduction of crashes is shown in Table 2.5.

Table 2.5. Effects of variable message signs on crash reduction (Elvik *et al.,* 2009)

Measure	Types of crashes effected	Percentage of reduction
Crash warning signs	Injury crashes	44%
Weather-controlled speed limits	Crashes in winter	13%
	Crashes in summer	2%
Queue warnings on motorways	Rear-end crashes	16%
Collective feedback signs for speed	All crashes	46%
Individual feedback signs for speed	All crashes	41%
Individual feedback signs for close following	Rear-end crashes	6%

2.8. Summary

The literature review revealed that a number of studies focusing on motorcyclist safety have been conducted in a number of countries to date. Most of these studies developed models to predict crash frequency or crash severity for motorcycles based on historical crash data and statistical methods. The key drawbacks of this traditional approach are that the movement characteristics of motorcycles are not fully considered and it is problematic to obtain reliable historical crash data for model development purposes.

As also revealed from the literature review, the use of traffic conflict technique as a surrogate measure has been evaluated and validated in a number of studies carried out in different countries. Several findings from the previous studies may be summarised as follows:

- There is strong relationship between the frequency of conflict and crash events (Amundsen and Hydén, 1977; Miglez, Glauz and Bauer, 1985; Hydén, 1987; Svensson, 1992; Archer, 2004; Gettman *et al.,* 2008; Ismail, 2010; Guo *et al.,* 2010).

- The causal mechanism for both conflict and crash events are similar (Guo et al., 2010).

- The effects of contributing factors on the occurrence of conflicts and crashes were not found to be different (Guo *et al.,* 2010).

From these points, it may be suggested that the traffic conflict analysis may be used in road safety assessment as a surrogate measure to overcome the limitations of traditional method which based on analysing historical crash data. According to Svensson (1992), the use of surrogate measures might be as good as actual crash data in estimating the expected number of crashes.

Moreover, the literature review also indicated that most of these studies focused on the conventional traffic environment found in high-income countries where passenger cars are the predominant vehicle type. Therefore, it seems to suggest that there is a lack of studies focusing on investigating the contribution of non-lane-based movement characteristics of motorcycles to motorcyclist safety in the traffic environment where the motorcycle is the predominant mode of transport.

There is a need therefore to obtain a surrogate measure to address the limitations of traditional approach and to develop a methodology to capture crash potentials associated with the unique movement behaviours of motorcyclist in motorcycle-dominated traffic environments. The preliminary results of the developed models may be used to support traffic engineers in improving urban road safety and developing appropriate countermeasures to mitigate the crash risk for motorcyclists. The literature review of studies on motorcyclist safety is summarised in Table 2.6.

Table 2.6. Summarisation of studies on motorcyclist safety assessment

Authors	Year	Traffic environments	Area	Modelling approach	Risk factors
Manan	2014	Motorcycle dominated	Urban /Rural	Surrogate measures	Speed, manoeuvre behaviour, rider gender, helmet use.
Shaheed *et al.*	2013	Conventional	Urban	Traditional	Roadway surface condition, clear vision, light conditions, speed limit, and helmet.
Manan *et al.*	2013	Motorcycle dominated	Urban	Traditional	Number of access points, presence of median, land use.
Daniello and Gabler	2011	Conventional	Urban /Rural	Traditional	Roadside objects
Nunn	2011	Conventional	Urban	Traditional	Roadside objects, risky behaviour,

					speed, alcohol and drugs, lighting, age of riders.
Rome *et al.*	2011	Conventional	Urban /Rural	Traditional	Helmet use and protective clothing, age and experiences of riders.
Schneider *et al.*	2010	Conventional	Rural	Traditional	Radius and length of horizontal curve, shoulder length.
Indriastuti and Sulistio	2010	Motorcycle dominated	Urban	Traditional	Rider gender, travel purpose, travel distance, rider experience, number of motorcycles owned.
Haque and Chin	2010	Conventional	Urban /Rural	Traditional	Road type, curbs, nighttime, red light cameras.
Haque *et al.*	2009	Conventional	Urban	Traditional	Errors, pavement surface, lighting, speed limit, pillion passenger, engine capacity, age of rider.
Haworth *et al.*	2009	Conventional	Urban /Rural	Traditional	Alcohol consumption, speeding, non-use of helmets and unlicensed riding.
Wanvik	2009	Conventional	Urban /Rural	Traditional	Road lighting, weather condition, road surface conditions.
Yeh and Chang	2009	Conventional	Urban /Rural	Traditional	Age, gender and experience of riders.
Li *et al.*	2008	Conventional	Urban /Rural	Traditional	Road type, gender and age of riders, helmet use.
Majdzadeh *et al.*	2008	Conventional	Urban /Rural	Traditional	Road conditions, gender and age of riders, weather conditions
Pai and Saleh	2008	Conventional	Urban	Traditional	Crash type, manoeuvre behaviour, junction control, engine size, speed limit, light condition, weather condition, age and gender of riders.
Elliott *et al.*	2007	Conventional	Urban	Traditional	Traffic errors, speed violations, stunts, safety equipment and control errors, age and experience.
Chang and Yeh	2007	Conventional	Urban	Traditional	Age and gender of riders, traffic violations, negligence of potential risk

Savolainen and Mannering	2007	Conventional	Urban /Rural	Traditional	Crash type, roadway characteristics, alcohol consumption, helmet use, unsafe speed.
Clarke *et al.*	2007	Conventional	Urban /Rural	Traditional	Crash type, curves, age and experience of riders
Harnen *et al*.	2006	Motorcycle dominated	Urban	Traditional	Speed, lane width, number of lanes, shoulder width and land use at junctions
Dandona *et al.*	2006	Conventional	Urban /Rural	Traditional	Drivers licences, helmet use, vehicles conditions
Lapparent	2006	Conventional	Urban	Traditional	Crash types, lighting, weather condition, gender and age of riders, helmet use
Keng	2005	Conventional	Urban /Rural	Traditional	Speed limit, weather condition, lighting, age and gender of riders, helmet use
Claret *et al.*	2005	Conventional	Urban /Rural	Traditional	Speeding, age and gender of riders, alcohol consumption, helmet use
Lin *et al.*	2003	Conventional	Urban /Rural	Traditional	Risky behaviour, alcohol consumption, traffic violations, age and experience of riders
Ferrando *et al.*	2000	Conventional	Urban	Traditional	Helmet use, age and gender of riders
Shankar and Mannering	1996	Conventional	Urban /Rural	Traditional	Roadway conditions, vehicle and rider characteristics

- *Conventional: conventional traffic environments where passenger cars are the predominant vehicle type;*
- *Motorcycle dominated: traffic environments where motorcycles are the predominant mode of transport;*
- *Traditional: the traditional road safety approach which is based on analysing historical crash data;*
- *Surrogate measure: the surrogate road safety approach which is based on analysing traffic conflicts.*

CHAPTER 3

METHODOLOGY

3.1. Introduction

The overall aim of this research is to improve road safety for motorcyclists in a motorcycle-dominated traffic environment of urban roads. To achieve this, it appears necessary to develop a model capable of capturing satisfactorily the potential of motorcycle crashes for this particular traffic environment with the view to identify treatment measures to prevent them. As stated in Chapter 1, in a motorcycle-dominated traffic situation, motorcycles perform non-lane-based movements which are distinct from lane-based movements of passenger cars in a conventional traffic environment. Although these movement characteristics are found to be the predominant cause for the majority motorcycles crashes in urban areas, it seems there are no models that take them into account explicitly.

To fulfil this gap, this research seeks to develop models to estimate the potential of rear-end and sideswipe crashes which are two major crash types associated with the non-lane-based movement behaviour of motorcyclists in a motorcycle-dominated traffic environment. The proposed models may support traffic engineers in detecting hazardous traffic locations associated with higher crash potentials and assessing their contributing risk factors with the aim to develop appropriate countermeasures to mitigate the crash risk for motorcyclists.

This chapter comprises six sections. The first section describes the overall approach of this research and the overall reasoning is outlined in the next section. The third section describes the modelling approach associated with the non-lane-based movement characteristics of motorcycles that may lead to the crash risk for motorcyclists. The fourth section presents the techniques that are used to develop crash risk models. The fifth section outlines the approach used to determine the contributing factors included in the models and the approach used to determine countermeasures is shown in the final section.

3.2. Overall Approach

The literature review revealed that a number of models and systems have been developed to date to estimate the frequency of motorcycle crashes or the severity of crashes in terms of injuries and fatalities or in measuring the relative risk of crashes (road scoring) based on the assessment of attributes related to the infrastructure, the traffic environment and the road users (Archer, 2004; Elvik *at al.*, 2009). However, the application of these tools may produce eroneous results because:

1. They are not appropriate for the motorcycle-dominated traffic situation which is common in a number of low-income and middle-income countries.
2. There is lack of satisfactory crash data and therefore it is felt that they may not capture satisfactorily motorcycles' crash types which have been found to account for the majority of motorcyclists' injuries and fatalities in urban environments (section 1.3).
3. They do not consider the non-lane-based movement characteristic of motorcycles which has been found to have a significant contribution to the occurrence of motorcycle crashes.

To address these three gaps, this study proposes a methodology to assess the motorcyclist safety focussing on:

1. The assessment of motorcyclist safety in a motorcycle-dominated traffic environment where motorcycle is the predominant mode of urban transport.
2. The estimation of the risk for rear-end and sideswipe crash types which are the two major types of motorcycles' crashes in urban areas (Manan and Várhelyi, 2012; Ming, Wucheng and Cheng, 2013; DoT, 2013).
3. The modelling of non-lane-based movement of motorcycles as a significant factor contributing to the potential of the above crash types (Long, 2012; Ming, Wucheng and Cheng, 2013; DoT, 2013).

It was therefore felt reasonable to suggest that to meet the above objectives, it was critical to understand the interactions between the elements of a traffic system as shown in Figure 3.1. The traffic system is complex and dynamic in nature due to the relationships amongst its elements that include the vehicles, the drivers, the road infrastructure and the overall road environment. Therefore, the occurrence of a road crash was considered as the result of inappropriate interactions between or amongst these components (Archer, 2004).

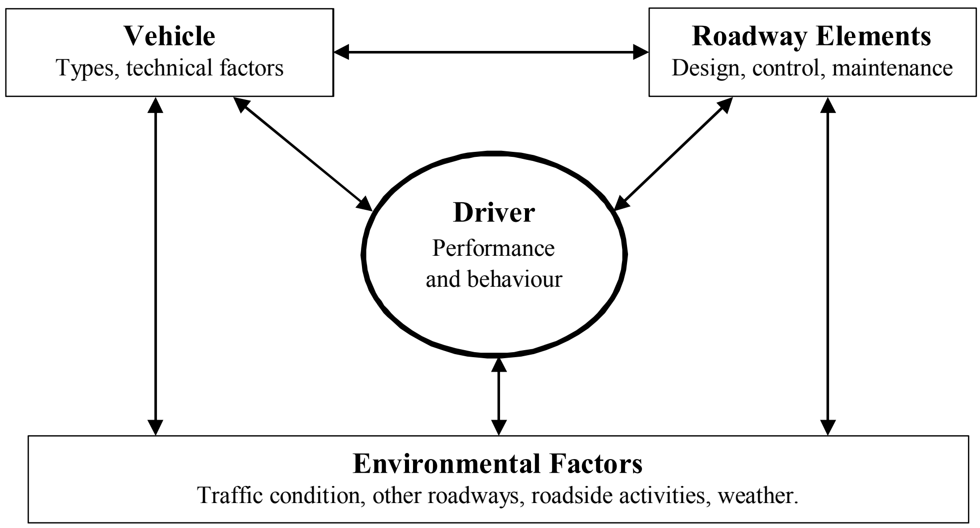


Figure 3.1. Interactions between elements in a traffic system (Archer, 2004)

Based on this system and by studying the major causation resulting in crashes, this study proposes a methodology to estimate the crash risk for motorcyclists resulted from the contribution of infrastructure (i.e. road attributes), traffic condition (i.e. motorcycle-dominated traffic environment) and road user behaviour (i.e. non-lane-based movement behaviour of motorcyclist). The contribution of vehicle-related factors were not considered as it was felt to be beyond the scope of this research.

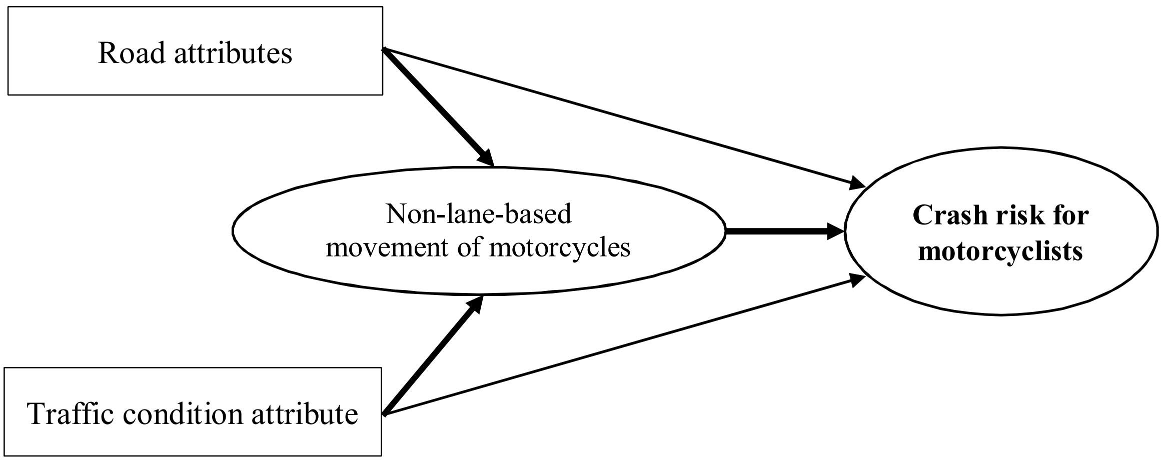


Figure 3.2. Attributes contributing to motorcyclist crash risk

To capture the contribution of these three components to crash risk, the non-lane-based movement behaviour of motorcyclists was chosen as the core of the modelling process in which the road environment and associated traffic conditions were the predominant factors affecting the movement characteristics of motorcycles and ultimately their crash potential (see Figure 3.2). Having assessed the crash potentials for a specific location using the above approach, countermeasures may be designed based on the assessment of the relative importance of risk factors contributing to the overall motorcycle crash risk. The overall approach of this process is shown in Figure 3.3.

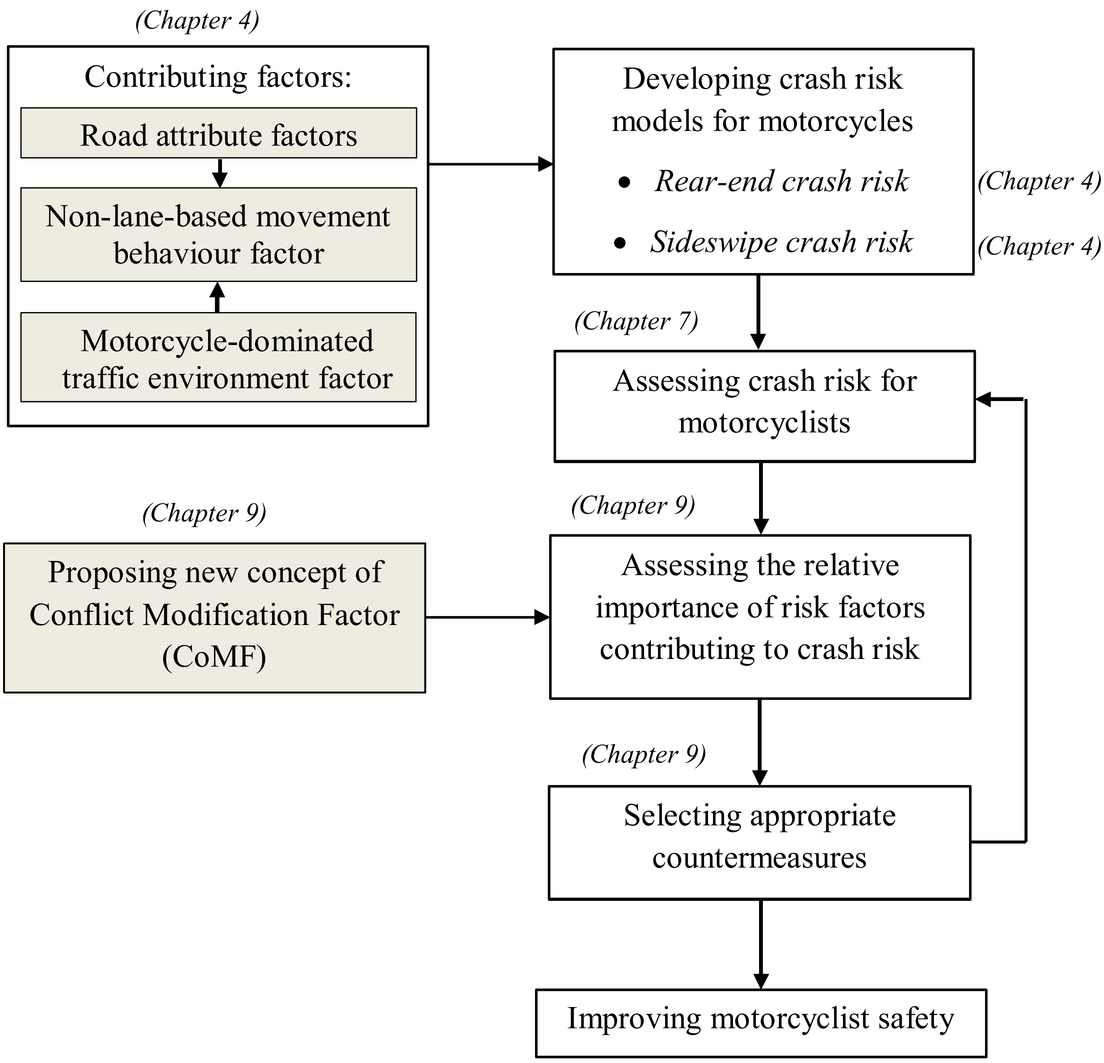


Figure 3.3. Overall approach to improve motorcyclist safety

3.3. Overall Reasoning

The first step of the above process is to develop appropriate crash risk models and use them as a tool to identify hazardous traffic locations in need of countermeasures. Two crash risk models that capture satisfactorily the majority of total motorcycle crashes associated with the movement characteristics of motorcycles are suggested in this research. The first model is for the rear-end crashes that may occur when a motorcycle follows the front vehicle in a short distance. The other one is for the sideswipe crashes that may occur when a motorcycle swerves to the left or the right suddenly and may be hit on the side by a vehicle following the motorcycle on its side. The second step of this approach uses the outputs of developed models to determine appropriate countermeasures to prevent the occurrence of crashes based on the concept of the Conflict Modification Factors (CoMF). This new concept is based on the change in the relative risk of the contributing factors and may be used as a measure to evaluate the effectiveness of the selected countermeasures.

However, the proposed theoretical models should be calibrated and validated using real data to be of practical use. Consequently, road segments from the city of Danang in Vietnam were chosen as representative of a motorcycle-dominated traffic environment for this purpose as Vietnam is a developing country where motorcycles constitute over 80% of total traffic on urban roads and motorcycle crashes account for nearly 70% of the total road crashes in urban areas. It is envisaged however that the proposed methodology may be transferable to similar environments where the motorcycle is the predominant mode of urban transport.

3.4. Definition of Non-lane-based Movements in the Modelling Process

To take into consideration the causation of non-lane-based movements resulting in crash potentials, it was critical to understand the characteristics of this particular movement as stated in Chapter 1. It is felt that due to their small size and flexible turning radius, motorcycles can manoeuvre relatively freely in the traffic stream. Particularly in a motorcycle-dominated traffic environment, motorcycles do not conform to lane discipline and tend to swerve to change their direction and speed frequently. Also, because they occupy a small space when travelling, motorcycles are able to travel alongside with other vehicles in the same car-lane as well as filter through the lateral clearances between vehicles (section 2.3.1). These movement characteristics were described to be as the non-lane-based movements characteristics of motorcycles (Minh, 2007; Lee, 2007; Long, 2012; Shiomi *et al.*, 2013). Such movements are found to be major causes of crashes for motorcyclists (Hsu, Sadullah and Dao, 2003; Amelia and Harnen, 2010; Long, 2012; Manan, 2014). As stated in Section 1.3, rear-end and sideswipe crashes resulted from these movements account for more than 20% and 30% of the total motorcycle crashes respectively. Consequently, the causation of these non-lane-based movements potentially resulting in the motorcycle crashes risk taken into account in this study may be illustrated in Figure 3.4.

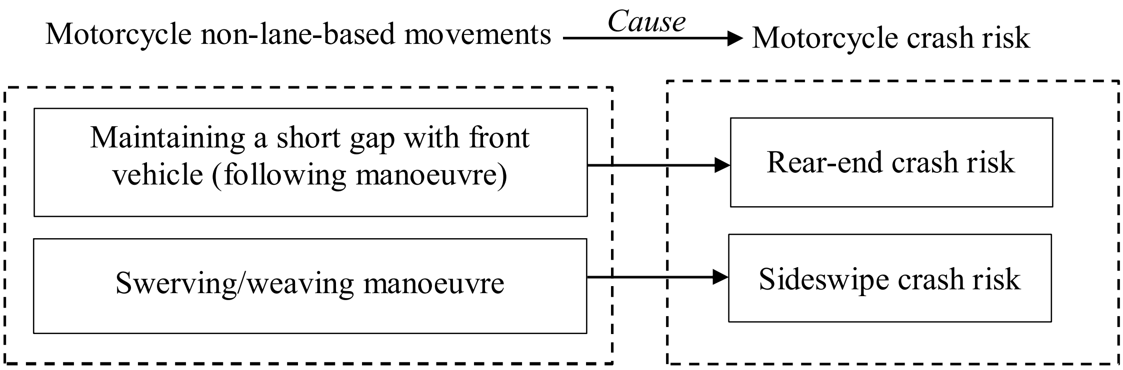


Figure 3.4. Consequence of non-lane-based movements resulting in crash risk

3.5. Techniques Used to Build Motorcycle Crash Risk Models

The method used to develop rear-end and sideswipe crash risk models was based on the discrete choice analysis and the traffic conflict technique. The former was adopted to capture the non-lane-based movement behaviour of motorcyclists that lead to the potential of rear-end and sideswipe crashes and the latter was employed as a surrogate measure to traditional approach to determine the occurrence of these two crash potentials. The use of discrete choice analysis and traffic conflict technique in this study is justified in the following sections.

3.5.1 Applying the discrete choice analysis

The use of the discrete choice analysis for modelling the non-lane-based movement behaviour of motorcyclists in this study may be justified as follows. First, non-lane-based manoeuvre behaviour may be regarded as a discrete choice decision made by the motorcyclists for their next movements under given traffic conditions generated by the surrounding vehicles. Therefore, it was felt that the discrete choice theory may capture this assumption satisfactorily. Second, the discrete choice models are designed to be calibrated on real data, thus the proposed models may be calibrated from real traffic data collected in the field.

The discrete choice analysis is a methodology used to model the choice from a set of mutually exclusive and collective options (Ben-Akiva and Lerman, 1985). A choice is defined as an outcome of a sequential decision-making process that includes the following steps: (1) defining the choice problem, (2) determining available options, (3) evaluating the attributes of these options, (4) choosing the most attractive option, and (5) implementing this choice. As presented by Ben-Akiva and Lerman (1985), the framework of discrete choice theory is defined by four components:

- The decision maker: denotes the decision-making entity which can be an individual person, group of people, a firm or an organization.
- The set of options (choice set): denotes available options that a decision maker considers during a choice process.

- Attributes of options: denote the attractiveness of the options of the choice set and each option is characterised by a set of attributes.
- Decision rules: denote the process used by the decision maker to choice an option from the choice set.

Based on this framework, a choice of a manoeuvre made by a motorcyclist may be viewed as an outcome of a sequential decision-making process that includes the following components (see Figure 3.5):

- The decision maker of this process is the motorcyclist who will evaluate available movement options to choose for his/her next path.
- The choice set consists of two movement options: keep the current direction (following manoeuvre and braking manoeuvre) or change the current direction (swerving manoeuvre).
- The attributes of the movement options: in order to choose either a following or a swerving manoeuvre, the motorcyclist will evaluate the current driving conditions with respect to the surrounding environment. The presence of neighbouring vehicles on the road directly affects the motorcyclists' decisions for their next movement choices. Therefore, the attributes of traffic condition will be included in the modelling process.

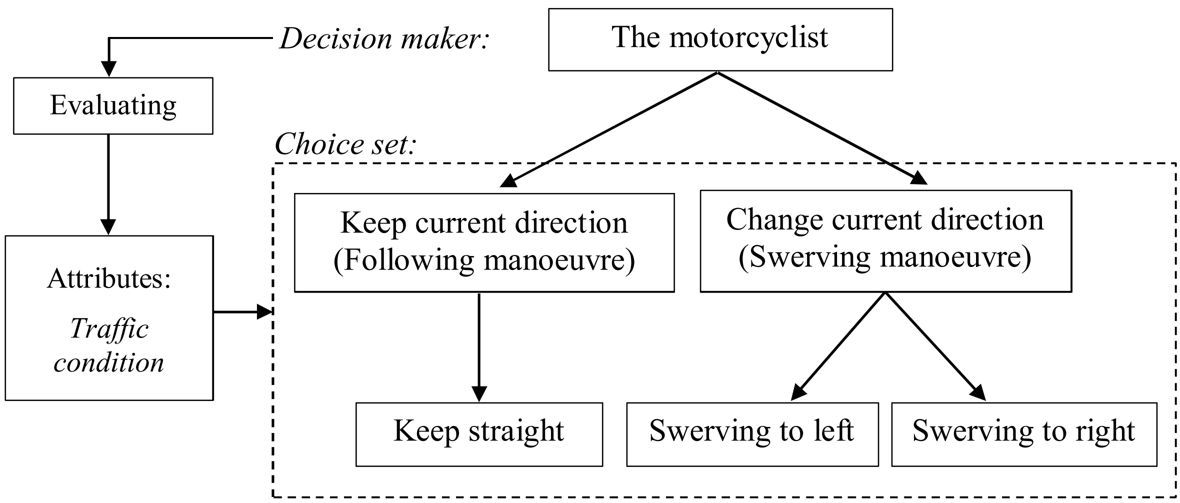


Figure 3.5. The process of choosing manoeuvre behaviour of motorcyclists

3.5.2 Applying the traffic conflict technique

The traditional methods for road safety assessment are based on historical crash data to build a safety performance function or a crash prediction model to estimate the expected crash frequency (Saunier, 2013). However, this method faces challenges regarding to obtaining a reliable data for model development process (see section 2.1.1). Therefore, there is a need for surrogate measures for road safety assessment that do not rely on historical crash data but:

1) they are related to traffic events that are more frequent than crashes and can be observed in the field; and
2) they are correlated to crashes logically and statistically.

As stated in Section 2.1.2, to fulfil this need, the traffic conflict technique has been proposed as a surrogate method to crash history data analysis (Amundsen and Hydén, 1977; Hydén, 1987; Svensson, 1998). Albeit not a better technique compared to those using crash data, according to Svensson (1998), the traffic conflict technique is an approach to estimate crash risk based on determining and measuring conflicts which have the characteristics of crashes, but where no crash actually results. Amundsen and Hydén (1977) defined a traffic conflict as "*an observable situation in which two or more road users approach each other in space and time to such an extent that there is the risk of crash if their movements remain unchanged*". According to this definition, a conflict event will lead to a crash if road users do not take sufficient evasive action to avoid it. Therefore, a crash is always preceded by a conflict and conflict events may be used as a measure to assess the likelihood of crashes (see Figure 3.6). Based on this approach, a motorcycle crash risk is defined in this study as a motorcycle conflict event potentially resulting in a crash if the motorcyclists involved in the conflict do not take evasive action properly.

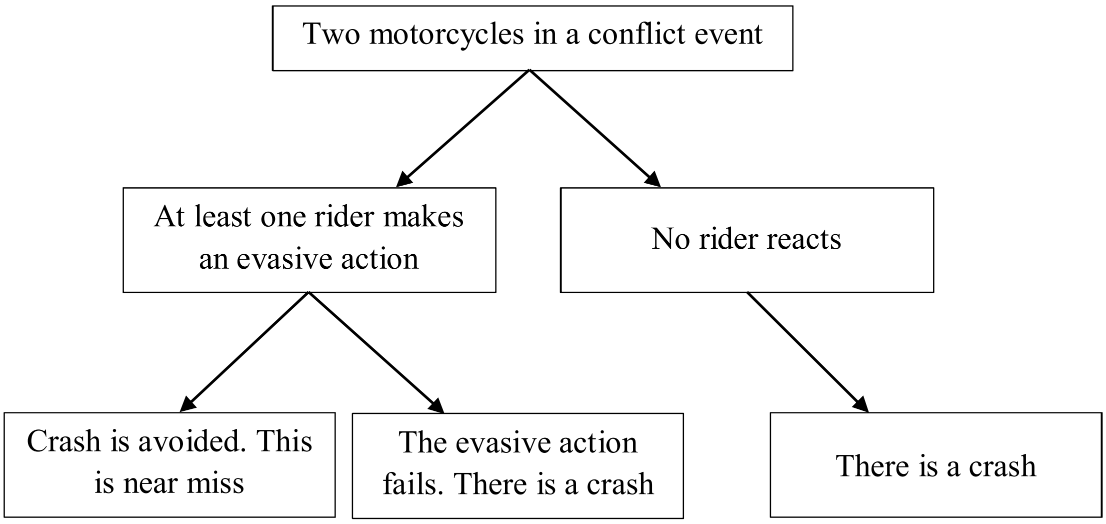


Figure 3.6. The conflict and crash events

In road safety analysis, using historical crash data is the most useful reactive approach. Good quality data are required for this to be reliable. However, in some LMICs good crash data are not readily available (Lynam, 2012; WHO, 2015) and alternative techniques must be used. Therefore to deal with this issue, it was felt necessary in this study to apply the traffic conflict technique as a surrogate measure to historical crash analysis method to determine the risk of rear-end and sideswipe crashes for motorcycles. The traffic conflict technique proposed to use in study was based on the following properties:

- There is statistical relationship between the frequency of conflict and crash events (Amundsen and Hydén, 1977; Miglez, Glauz and Bauer, 1985; Hydén, 1987; Svensson, 1992; Archer, 2004; Gettman *et al.,* 2008; HSM, 2009; Ismail, 2010; Laureshyn, 2010; Guo *et al.,* 2010). Gettman *et al.* (2008) found that the ratio of traffic conflicts to actual crashes may be 20,000 to 1.
- The causal mechanisms for both conflict and crash events are similar (Guo *et al.,* 2010). According to Laureshyn (2010), the occurrence of a crash is always proceeded by a conflict.
- The effects of contributing factors on the occurrence of conflicts and crashes do not seem to be different (Guo *et al.,* 2010).

In addition, the use of traffic conflict technique in this study was further supported by the following three reasons:

- The traffic conflict technique is based on observing the interactions of road users in the field, therefore this method may be used to assess the contribution of non-lane-based movement behaviour of motorcyclists to crash potentials.
- Traffic conflicts are more frequent than crashes and therefore the data needed for assessing motorcycle crash risk can be collected in a short period time using video recordings (Ismail, 2010; Laureshyn, 2010). In addition, road safety improvement as a result of countermeasures for a specific location may be evaluated quickly based on the observation of traffic conflicts (Guo et al., 2010).

- Traffic conflicts are observable events, therefore both traffic condition features and road environment factors that contribute to crash potentials can be studied, as all these data can be obtained together with traffic conflict events in the field (Ismail, 2010; Laureshyn, 2010).

To determine a traffic conflict event, several measures have been developed to date. One of the most commonly known measures is "Time-to-Collision" (TTC) which was initially proposed by Hayward (1972). TTC is defined as "*the time that remains until a crash between two vehicles would have occurred if the crash course and speed difference are maintained*" (Hayward, 1972). This measure was then utilised by several researches for traffic safety assessment (Hyden, 1987; Hayward, 1972; Sayed et al., 1994). For vehicles manoeuvring in the same direction, TTC can be calculated by:

$$TTC = \frac{(P_L - P_F) - L_L}{v_F - v_L}$$

(Equation 3.1)

where, P_L and P_F are the positions of the leading and following vehicles respectively, L_L is the length of the leading vehicle, v_L and v_F are the speeds of the leading and following vehicles respectively.

The major advantage of TTC is that it is a very simple time-based indicator in use and calculation, and therefore this measure has been used widely in traffic safety studies (Wang, 2013). However, TTC still has the following drawbacks.

- TTC is implicitly represented by the time-value derived from measures of speed and distance (Equation 3.1). This implies that all minimum TTC values of, for example, 1.0 second are regarded as having an equal level of severity irrespective of whether the speed used in the calculation is 10 km/h or 100 km/h. The TTC concept may therefore be less useful as a comparative measure of crash risk (Archer, 2004; Ismail, 2010; and Wang, 2013).

- TTC does not consider the potential evasive actions after the conflict occurrence. The fact is that drivers have varied reaction times and vehicles have varied braking abilities under different speed levels and road surface conditions. Therefore, different conflict types can have different levels of crash potentials with the same TTC. Even for the same conflict type, different speeds can pose different levels of difficulty for drivers to avoid the conflict as well as different levels of crash severity (Archer, 2004; Ismail, 2010; and Wang, 2013).

Therefore, to fulfil the above two gaps, the concept of Stopping Distance (SD) was suggested as a measure to determine traffic conflicts. The SD concept was originally proposed by Allen, Shin and Cooper (1978) and thereafter has been adopted by a number of researchers for traffic safety assessment (Gettman and Head, 2003; Oh, Park and Ritchie, 2006; Son, Kweon and Park, 2008). Oh, Park and Ritchie (2006) proposed a Stopping Distance Index based on the concept of Stopping Distance to assess the potential of rear-end crashes. According to them, to avoid rear-end collisions, the stopping distance of the leading vehicle should be larger than that of the following vehicle and may be calculated as follows:

$$v_L * h + \frac{v_L^2}{2a_L} > v_F * \tau + \frac{v_F^2}{2a_F}$$

(Equation 3.2)

where, v_L and v_F are the speeds of the leading and following vehicle respectively, a_L and a_F are the braking deceleration of the leading and following vehicle respectively, h is the time headway between the two vehicles, τ is the reaction time of drivers.

As illustrated in Equation (3.1) and (3.2), the "Time-To-Collision" concept is defined as a function of speed and distance while the "Stopping Distance" concept is calculated as a function of vehicle speed, driver time reaction and vehicle braking deceleration. Therefore, for the purpose of this study, to evaluate the effect of the unique characteristics of motorcycles (e.g. braking reaction time, maximum braking deceleration) on crash risk that are distinct from other vehicle types (see sections 2.3.3 and 2.3.3), this study adopted the concept of Stopping Distance to calculate Threshold Safety Distance (TSD) indicators in order to determine the rear-end and sideswipe conflicts.

3.6. Risk Factors Determination Approach

Any factor that increases the probability of crash occurrence and crash severity is a risk factor and it is statistically related to crash frequency and severity (Elvik *et al.,* 2009). These risk factors affect the consequence of events before, during and after a crash period (HSM, 2009; WHO, 2013). Therefore the main aim of road safety analysis is to investigate risk factors associated with the occurrence of a crash with the view to identify appropriate countermeasures to mitigate crash frequency and severity (HSM, 2009; Elvik *et al.,*2009; WHO, 2013). To achieve this, it is necessary to understand the cause and effect relationships related to crash probabilities.

The occurrence of a road crash is the result of a series of events effected by a large number of risk factors related to the components of the traffic system. Haddon (1980) developed a matrix to identify risk factors before, during and after the crash related to human, vehicles and the environment as shown in Table 3.1. Haddon's matrix assists in understanding driver behaviour, road environment and vehicle factors that influence the frequency and severity of crashes. Once risk factors associated with crashes are identified and evaluated, appropriate countermeasures may be developed to prevent the occurrence of crashes and their severities.

For the pre-crash phase (before-crash period), countermeasures are determined to prevent the crashes from occurring. The crash phase (during-crash period) is related to interventions that reduce the severity of crashes if they occur. The post-crash phase (after-crash period) is associated with measures that mitigate the outcome of crashes after they have occurred.

Table 3.1. The Haddon Matrix (Haddon, 1980)

Phase		Human factors	Vehicle factors	Environment factors
Pre-crash	*Factors contributing to increased risk of crash*	Distraction, fatigue, poor judgment, age, alcohol and drug use, experience and skill, driving behaviour.	Worn tyres, lighting, braking, handling, speed management.	Road geometry, signs and markings, road surface, surroundings, traffic condition, speed limits.
Crash	*Factors contributing to crash severity*	Vulnerability to injury, age, failure to wear a seat belt, driving speed, sobriety.	Occupant restraints, other safety devices, crash protective design.	Pavement friction, grade, roadside environment.
Post-crash	*Factors contributing to crash outcome*	Age, gender.	Ease of removal of injured passengers, fire risk.	Emergency response, medical treatment.

Based on Haddon's approach, this study seeks to identify and evaluate critical risk factors related to the pre-crash and crash phases by considering human and environment factors as shown in Table 3.2. When the effects of these risk factors on motorcycle crash potentials are determined and investigated, infrastructure solutions and traffic control measures may be subsequently designed to reduce the motorcyclist crashes risk.

Table 3.2. Risk factor included in crash risk models for motorcycles

Phase		Human factor	Environment factor
Pre-crash	*Factors contributing to increased risk of crash*	• Manoeuvre behaviour of motorcyclists • Operating speed	• Traffic condition • Road condition
Crash	*Factors contributing to crash severity*	• Operating speed	• Traffic condition • Road condition

3.7. Countermeasure Selection Approach

It has been suggested that the safety of a traffic system may be measured by the three basic dimensions: exposure, crash rate and injury severity (OEDC, 1997; Nilsson, 2004; Archer, 2004; Elvik *et al.,* 2009). The exposure denotes the magnitude and character of the activities that generate the crashes. Therefore, the exposure may be measured by the number of trips (traffic volume), the types of transport (pedestrians, cyclists, motorcyclists, car occupants or public transport) and the traffic environments (e.g. motorcycle dominated traffic). Crash rate refers to the frequency of crash occurrence and defined as the risk of crash per unit of exposure. Injury severity refers to the consequence of crashes in terms of injuries or property damage. Changes in any one of these three dimensions, will influence the entire safety situation. By focusing on these safety dimensions, Elvik *et al.* (2009) proposed the taxonomy of factors affecting the number of injuries and fatalities in road crashes (see Figure 3.7) and suggested ways of improving road safety by: (1) reducing the exposure to crash risk by reducing the number of trips or shifting to transport modes that have a lower level of risk, (2) reducing the crash rate by implementing countermeasures related to risk factors, (3) reducing injury severity by increasing the protective measures for road users.

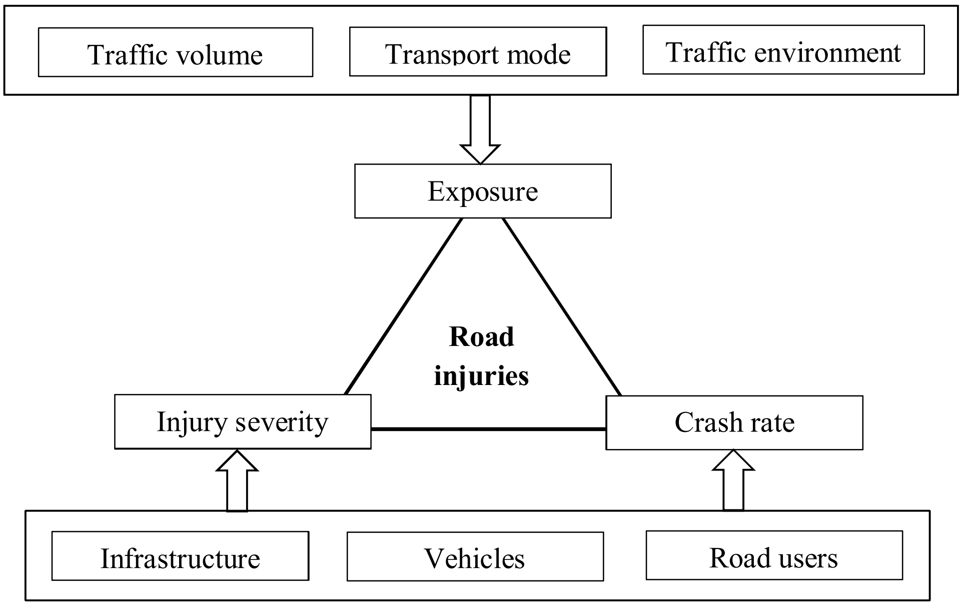


Figure 3.7. A taxonomy of factors affecting road safety (Elvik *et al.,* 2009)

Based on this approach, this study focused on reducing motorcycle crash potentials by selecting countermeasures to target specific risk factors related to the road environment factor and road user as shown in Table 3.2. Countermeasures to reduce the crash risk may include:

- **Road improvement and maintenance:** This measure may reduce or eliminate crash risk by improving and maintaining the transport system in terms of road design and road equipment. For example, improving sight distance and road surface friction, redesigning junctions, maintaining pavements, road lighting, road signs and markings, and correcting erroneous traffic signs (HSM, 2009; Elvik *et al.,* 2009; iRAP Toolkit, 2015).

- **Traffic control**: This measure may reduce crash risk by intervening in traffic conditions. For example, speed limits, installing road markings and variable message signs, providing segregated motorcycle lane, and applying the intelligent transport systems (ITS) (Elvik et al., 2009; iRAP Toolkit, 2015).

- **Policy/Legislation and Enforcement**: This measure may reduce crash risk by influencing the driving behaviour of road users and road designs. For example, mandating helmet wearing, requiring minimum design standards, penalising illegal behaviour such as excessive speeding and drunken driving, and installing automatic speed enforcement (HSM, 2009; Elvik et al., 2009).

- **Education**: This measure may reduce crash risk by influencing the driving behaviour of road users such as education programmes in school, driver training programmes and public awareness campaigns (HSM, 2009; Elvik et al., 2009).

- **Public transport mode shifting:** Public transport is, overall, a very safe mode of transport. Compared with riding a motorcycle, public transport has a considerably lower level of risk. For example, Savage (2013) conducted a research to compare the fatality risks in the United States for various modes of transport and they found that passenger fatalities per billion passenger-miles for riding a motorcycle and public transport mode (e.g. bus) are 212.57 and 0.11 respectively. Therefore, shifting to public transport may be a preferred solution to reduce crash risk of private transport modes such as motorcycles.

While all of the above countermeasures play an important role in reducing crash risk, the majority of these measures are beyond the scope of this research. This study focuses on the reduction of motorcycle crash potentials where it is believed that the road environment and traffic condition are contributing factors, either exclusively or through interactions with the movement behaviour of motorcyclists. Based on the crash risk models developed in this research, the effect of risk factors on crash risk is assessed and countermeasures related to risk factors subsequently may be determined to mitigate their contribution to crashes.

3.8. Conclusion

This chapter presented a methodology to estimate the potentials of both rear-end and sideswipe crashes for motorcycles based on an assessment of traffic conflict events associated with the non-lane-based movement characteristics of motorcycles in a motorcycle-dominated traffic environment of urban roads. The discrete choice model and the traffic conflict technique are proposed to build the model forms. This modelling approach will be applied to overcome the limitation of traditional road safety analysis which is based on historical crash data. The developed models may then be used to support traffic engineers in designing appropriate countermeasures to mitigate the crash risk for motorcyclists. The proposed methodology is expected to provide a better understanding of the effect of non-lane-based movement characteristic of motorcycles on crash potential, and to trigger further research on road safety assessment for motorcyclists in low-income and middle-income countries where motorcycles are the predominant mode of urban transport system.

CHAPTER 4

MODEL DEVELOPMENT

4.1. Introduction

This chapter presents the development process of a rear-end and a sideswipe crash risk model for motorcycles moving in a motorcycle-dominated traffic environment of urban roads. The chapter is organised in three main sections. The first section describes the modelling framework to develop the risk of rear-end and sideswipe crashes. The second section presents the model formulation of these two crash types. The third section describes the components included in the formulation of these models.

4.2. Modelling Framework

When travelling on roads, a motorcyclist has three choices for his/her manoeuvre: keep following the front vehicle, swerve to the left or swerve to the right to overtake the front vehicle as shown in Figure 4.1. When following the front vehicle, a rear-end crash may occur if the front vehicle suddenly decelerates while the subject motorcyclist maintains an inadequate distance that does not allow the subject motorcyclist to take an evasive action to avoid crashing with the front vehicle. When swerving to the left or the right, a sideswipe crash may occur if the available gap between the subject motorcycle and the laterally-following vehicle is less than the distance needed for the laterally-following vehicle to take evasive action to avoid crashing with the subject motorcycle. Using this assumption, to capture the potentials of these crash types for motorcycles moving in the traffic stream, a rear-end and a sideswipe crash risk model may be developed.

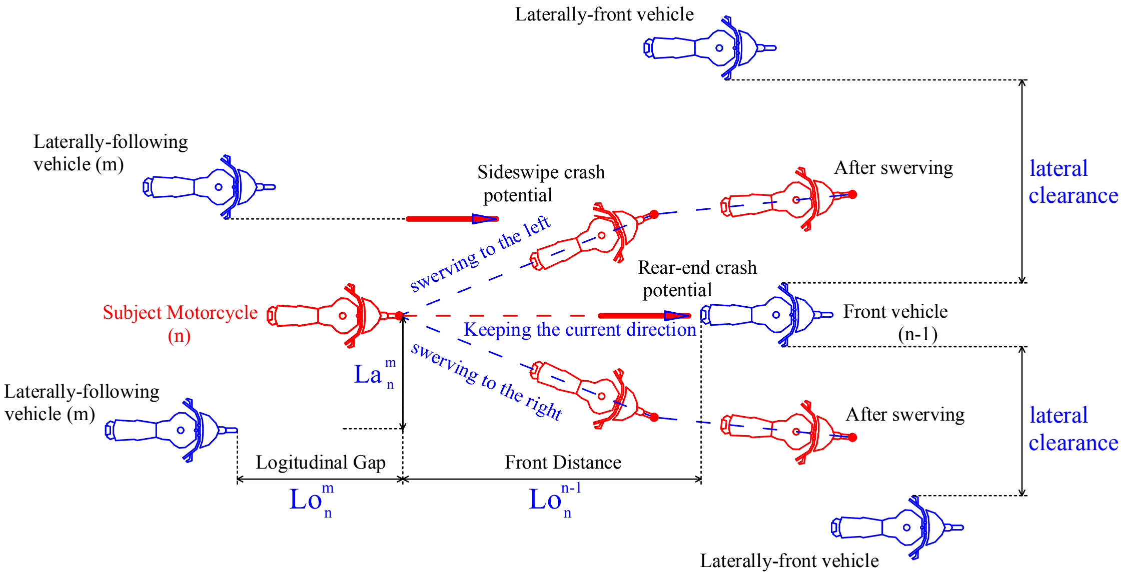


Figure 4.1. Movement scenarios of motorcycles in the traffic

The crash risk is defined in this research as a conflict potentially leading to a crash if the motorcyclists involved in the conflict do not take evasive action properly. Under this assumption, two types of conflicts are considered in this study (See Figure 4.2).

- a rear-end conflict, occurring when a motorcyclist follows a front vehicle in a short distance that cannot allow the motorcyclist apply a brake to avoid a potential rear-end crash with the front vehicle.
- a sideswipe conflict, occurring when a motorcyclist swerves to left or right and causes a potential sideswipe crash with the laterally-following vehicle.

To build model forms for describing rear-end and sideswipe crash risk, this study uses the logistic regression model and the lognormal distribution function. The former is adopted to capture the manoeuvre behaviour of motorcyclists potentially causing an interaction and the latter is employed to identify the occurrence of conflicts potentially resulting in crashes. The risk of a crash may be illustrated as the consequence of two independent events:

- the cause resulting in a potential conflict, and
- the condition in which the conflict may occur.

In the context of this study, the cause of a conflict is defined as the risky movement of the motorcycle and the condition for a conflict to occur is the inadequate gaps maintained between motorcycles. Therefore, the proposed crash risk models are formed by the joint probability:

- the probability of the causes leading to the conflict, and
- the probability of the condition resulting in the conflict occurrence.

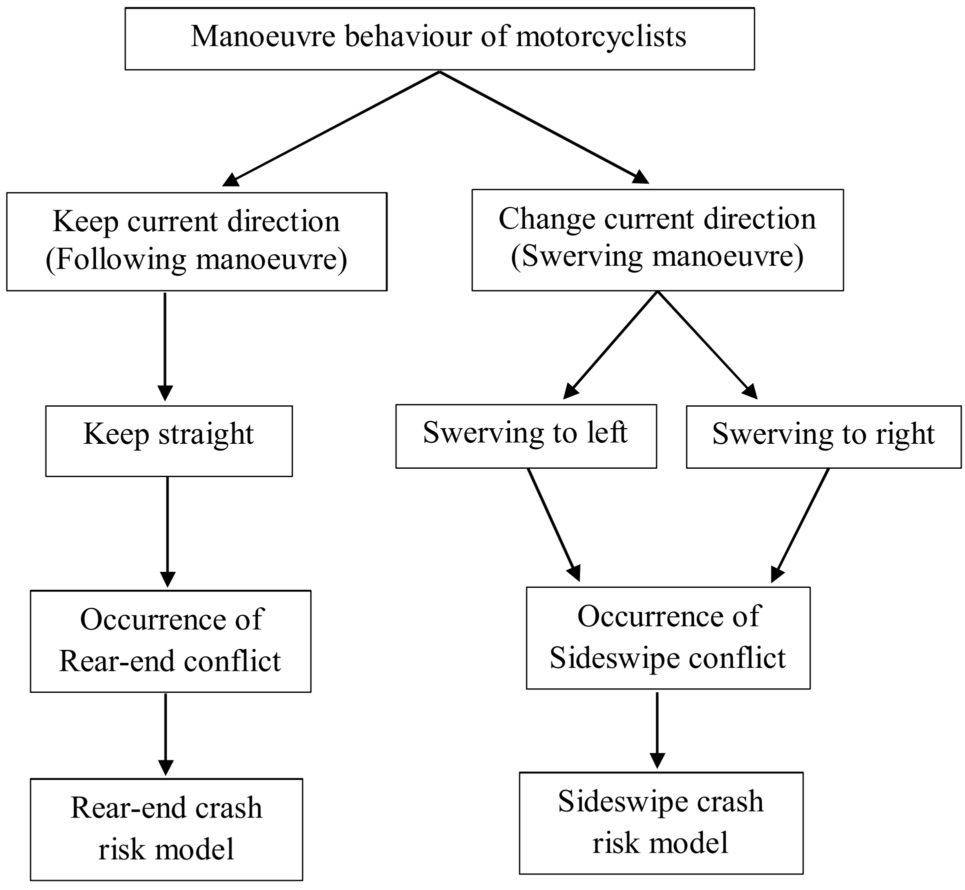


Figure 4.2. Modelling Framework

4.3. Model Formulation

This section presents the overall form of the rear-end and the sideswipe crash risk models. The components included in these models are presented in detail as follows.

4.3.1 Rear-end crash risk model

This model is developed to capture the potential of a rear-end crash for the motorcycle when it follows the front vehicle with an inadequate gap in the traffic stream. The potential of a rear-end crash for a motorcycle (n) moving in a motorcycle-dominated traffic situation may be defined as the result of a series of events:

- the subject motorcycle (n) keeps its current direction to follow the front vehicle (n-1) with a front distance (Lo_n^{n-1}),
- the front vehicle suddenly slows down,
- the subject motorcycle must decelerate to reduce its speed to avoid a possible rear-end crash with the front vehicle,
- a rear-end crash potential occurs if the front distance is less than the proposed threshold-safety-distance ($\mathrm{D}_{\mathrm{TSD}}^{\mathrm{FM}}$) and it potentially leads to a crash if the motorcycles involved in the conflict do not take proper evasive action.

Under the assumption that these events are independent, the risk of a rear-end crash that may occur at a point of time t under a given traffic condition X (e.g. high traffic density) may be estimated by the joint probabilities of these events as follows:

$$Pr(RE_{n-1}^{n}) = Pr\,(FM_n|X) \times Pr\,(FM_{n-1}|X) \times Pr\,(C_n^{n-1}|D_{TSD}^{FM})$$

(Equation 4.1)

where,

- $Pr(FM_n|X)$: is the probability that the subject motorcycle (n) will keep its current direction under a given traffic condition X.
- $Pr(FM_{n-1}|X)$: is the probability that the preceding vehicle (n-1) will keep its current direction under a given traffic condition X.
- $Pr(C_n^{n-1}|D_{TSD}^{FM})$: is the probability of rear-end conflict occurring between the subject motorcycle (n) and the front vehicle (n-1).

4.3.2 Sideswipe crash risk model

This model is developed to capture the potential of a sideswipe crash for the motorcycle when it performs a swerving manoeuvre in the traffic stream. The potential of a sideswipe crash for a motorcycle (n) moving in a motorcycle-dominated traffic situation may be defined as the result of a series of events:

- the subject motorcycle (n) swerves to the left or right to overtake the front vehicle,
- the laterally-following vehicle (m) must decelerate to reduce its speed to avoid a possible sideswipe crash with the subject motorcycle,
- a sideswipe crash potential occurs if the longitudinal gap ($\mathrm{Lo}_\mathrm{n}^\mathrm{m}$) is less than the threshold safety distance ($\mathrm{D}_\mathrm{TSD}^\mathrm{SM}$) and it potentially results in a crash if the motorcycles involved in the conflict do not take proper evasive actions.

Under the assumption that these events are independent, the potential of a sideswipe crash may occur at a point of time t under a given traffic condition X (e.g. high traffic density) may be estimated by the joint probabilities of these events as follow:

$$Pr(SW_n^m) = Pr\,(SM_n|X) \times Pr\,(FM_m|X) \times Pr\,(C_n^m \middle| D_{TSD}^{SM})$$

(Equation 4.2)

where,

- $Pr(SM_n|X)$: is the probability that the subject motorcycle (n) will swerve to the left and right under a given traffic condition X.
- $Pr(FM_m|X)$: is probability that the laterally-following vehicle (m) will keep its current direction under a given traffic condition X.
- $Pr(C_n^m \middle| D_{TSD}^{SM})$: is the probability of sideswipe conflict occurring between the subject motorcycle and the laterally-following vehicle (m).

4.4. Model Components

To use Equations (4.1) and (4.2), two probabilities should be calculated:

- the probabilities that the subject motorcycle chooses either a swerving or a following manoeuvre to perform in a given traffic condition, and
- the probabilities that the conflicts occur between the subject motorcycle with the front vehicle or with the laterally-following vehicle when it performs a following or a swerving manoeuvre.

To obtain these probabilities, a manoeuvre choice model and conflict occurrence models are developed. These are presented in the following sections.

4.4.1 Manoeuvre choice model

To capture the probability that the subject motorcycle chooses either a swerving manoeuvre or a following manoeuvre to perform in a given traffic condition, a manoeuvre choice model is developed based on the discrete choice analysis method using the logistic regression model (section 3.5.1). The process of model development is conducted in the following two steps (A and B).

Step A: Identification of factors affecting manoeuvre choice

It appears that before deciding to choose a path to travel in the traffic stream, drivers normally evaluate the current driving conditions with respect to the relation with the surrounding vehicles. In other words, the presence of neighbouring vehicles on the road directly affects the subject drivers' decisions for their movement choices (Toledo, 2003). It therefore seems reasonable to suggest that the riding behaviour of the motorcyclist depends on the relative positions and relative speeds of the subject motorcycle with respect to its surrounding vehicles, including: the front vehicle, the laterally-following vehicles and other vehicles defining gaps in traffic. From this assumption, it may be seen that there are several significant factors involved in the decision-making process of motorcyclists choosing their manoeuvre behaviour, as follows:

1. **The speeds of front vehicles**: This factor reflects the driving conditions in the current direction of the motorcyclists. If the motorcyclists are satisfied with the speed of the vehicles ahead, they will keep their current direction and follow the front vehicles. Otherwise, they will decide to change their direction by swerving to the left or right to overtake the front vehicles.

2. **The lateral clearances between the front vehicles**: If the motorcyclists are not satisfied with the current positions and they feel the lateral clearance spaces between the front vehicles are large enough to move in, they will swerve to move toward these

positions, otherwise, they will keep their current direction and wait for a chance to swerve.

3. **The relative distances with respect to the surrounding vehicles**: When travelling in the traffic, the motorcycles are constrained by their neighbouring vehicles in front and side. This will affect their movement decisions. For example, if the motorcyclists feel the relative distances with the front vehicles are too short and the gaps with the laterally-following vehicles are large enough, they will choose to swerve to overtake the front vehicles, otherwise, they are likely to keep their current directions.

4. **Type of vehicles in the front or aside**: In a mixed traffic environment, it seems that the type of front vehicles and laterally-following vehicles affecting the manoeuvre choice behaviour of motorcyclists. The observations of motorcycles movement in the field reveal that they tend to choose swerving manoeuvre if the laterally-following vehicle is a motorcycle rather than a passenger car.

5. **Other contributing factors**: Other factors that may affect the riders behaviour such as their knowledge and experience, alcohol or drugs consumption, their ages and gender, their risk taking and the motorcycle's capabilities. In most cases, this information is not available and cannot be directly measured from vehicles' trajectory data in the field, therefore these factors are not considered in this study.

Step B: Model formulation development

As stated in Section 2.3.1, swerving manoeuvre is a typical behaviour representing the non-lane-based movement of motorcycles and it is captured based on the discrete choice analysis method (see section 3.5.1). In the context of this study, the choice of a manoeuvre behaviour made by a motorcyclist may be viewed as an outcome variable consisting of two alternatives: following manoeuvre or swerving manoeuvre. This outcome variable is of the binary type, and therefore the binary logistic regression model may be used to build the model equation.

Logistic regression analysis of the discrete choice theory is a method used to find the best fitting model to describe the functional relationship between an outcome (dependent or response variable) and a set of independent (predictor or explanatory) variables. The logistic regression model is used when the outcome variable is binary (Hosmer and Lemeshow, 1989).

In the logistic regression analysis method, the key quantity is the mean value of the outcome variable, given the value of the independent variables. This quantity is called the conditional mean and will be expressed as E(Y|x), where Y denotes the outcome variable and x denotes a value of the independent variable. If let the conditional probability that the outcome is presence be denoted by $P(Y=1|x) = \pi(x)$, then the logit of the logistic regression model for a collection of n independent variables $x_i = (x_1, x_2, \ldots, x_n)$ is given by (Hosmer and Lemeshow, 1989):

$$g(x_i) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_n x_n$$

(Equation 4.3)

in which case

$$\pi(x_i) = \frac{e^{g(x_i)}}{1 + e^{g(x_i)}}$$

(Equation 4.4)

where, $\beta = (\beta_1, \beta_2, \ldots \beta_n)$ are the coefficients of the independent variables.

By applying the logistic regression model in this study, the outcome variable stands for the manoeuvre choice of motorcyclists and is of the binary type, which is coded with a value of 1 to indicate the subject motorcyclist choose swerving manoeuvre, or zero to indicate that the subject motorcyclist choose following manoeuvre. The independent variables that may affect this outcome variable include: the relative speed with the front vehicle ($V_{\mathrm{n}}^{\mathrm{n-1}}$), the relative distance with the front vehicle ($Lo_{\mathrm{n}}^{\mathrm{n-1}}$), the lateral clearance spaces of the front vehicle (La_{n-1}), the relative speed of the laterally-following vehicle ($V_{\mathrm{n}}^{\mathrm{m}}$), the longitudinal gaps *(Lo_{n}^{m})* with the laterally-following vehicle, the type of the front vehicle (Te_{n-1}) and type of the laterally-following vehicle (Te_{m}). In a motorcycle dominated traffic environment, the type of front vehicle and laterally-following vehicle may be a motorcycle or a passenger car. Heavier vehicles such as buses or trucks were not considered in this study. These variables are shown in Figure 4.3.

Therefore, the logit of the logistic regression model *$g(x_i)$* may be formulated as a function of a set of seven independent variables x_i = ($Lo_{\mathrm{n}}^{\mathrm{n-1}}$, $V_{\mathrm{n}}^{\mathrm{n-1}}$, Lo_{n}^{m}, $V_{\mathrm{n}}^{\mathrm{m}}$, La_{n-1}, Te_{n-1}, Te_{m}) as follows:

$$g(x_i) = \beta_0 + \beta_1 Lo_n^{n-1} + \beta_2 V_n^{n-1} + \beta_3 Lo_n^m + \beta_4 V_n^m + \beta_5 La_{n-1} + \beta_6 Te_{n-1} + \beta_7 Te_m$$

(Equation 4.5)

where, $Lo_{\mathrm{n}}^{\mathrm{n-1}}$ is the front distance between the subject motorcycle (n) and the front vehicle (n-1), V_n^{n-1} is the relative speed between the subject motorcycle (n) and the front vehicle (n-1) ($V_n^{n-1} = V_n - V_{n-1}$), La_{n-1} is the lateral clearance of the front vehicle (n-1), Lo_n^m is the longitudinal gap between the subject motorcycle (n) and the laterally-following vehicle (m), V_n^m is the relative speed between the subject motorcycle (n) and the laterally-following vehicle (m), Te_{n-1} *and* Te_m are the type of the front vehicle (n-1) and the laterally-following vehicle (m) respectively (e.g. motorcycle or passenger car), and β_0, β_1, β_2, β_3, β_4, β_5, β_6, β_7 are unknown coefficients of independent variables to be estimated from the real data.

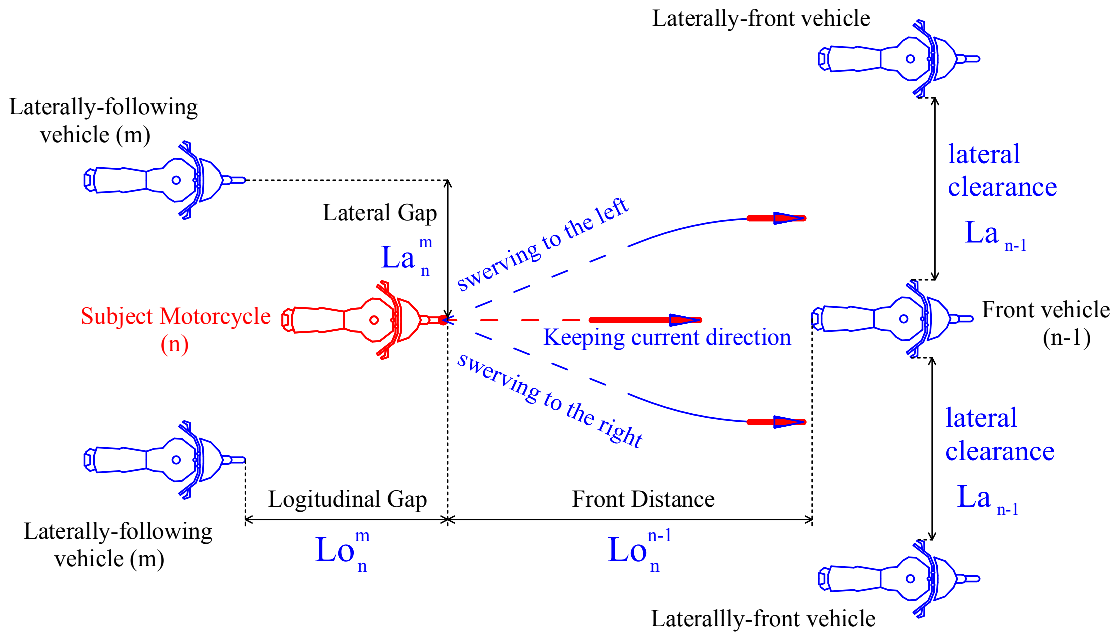


Figure 4.3. Independent variables of the manoeuvre choice model

Using Equation (4.5), the probability that a motorcycle chooses a swerving manoeuvre to perform in a given traffic condition X represented by a set of x_i independent variables is given by (Hosmer and Lemeshow, 1989):

$$Pr(SM_n|X) = \frac{e^{g(x_i)}}{1 + e^{g(x_i)}}$$

(Equation 4.6)

Also, the probability that a motorcycle chooses to follow the front vehicle in a given traffic condition X is as follows:

$$Pr(FM_n|X) = 1 - Pr(SM_n|X) = 1 - \frac{e^{g(x_i)}}{1 + e^{g(x_i)}} = \frac{1}{1 + e^{g(x_i)}}$$

(Equation 4.7)

The values of the probability of swerving manoeuvre choice presented in Equation (4.6) can take any value between 0 (‘Do not choose swerving manoeuvre’) and 1 (‘Choose swerving manoeuvre’), but it cannot exceed the range of 0 and 1.

4.4.2 Conflict occurrence models

To obtain the probabilities of the conflicts occurring presented in Equation (4.1) and (4.2), two conflict occurrence models are developed. The model development process is based on the concept of the Threshold-Safety-Distance (TSD) which is used as an indicator to determine the occurrence of conflicts. The model building process is described as follows (Step A and B).

Step A: Development of Threshold-safety-distance indicators

The threshold-safety-distances (TSD) are determined based on incorporating the stopping distance of a vehicle and the two manoeuvre scenarios of the motorcycles.

Stopping distance

The stopping distance may be defined as the sum of the reaction distance of the driver and the braking distance of the vehicle (AASHTO, 2004). Reaction time is the time that drivers need from the instant they recognise the danger ahead to the instant that they actually apply the brake. The braking distance of a vehicle is the distance needed from the instant that the driver begins applying the brake to stop the vehicle. The stopping distance may be formulated from the kinematic equation as follows (AASHTO, 2004):

$$d = v\tau + \frac{v^2}{2a}$$

(Equation 4.8)

where, τ, v and a are the reaction time, initial speed and braking deceleration respectively.

Threshold-safety-distance (TSD) indicators

The calculation method of the threshold-safety-distances is based on the critical condition in an emergency situation where it is assumed that a vehicle must stop to avoid a possible crash with the front vehicle or swerving motorcycle. In this study, two such indicators are developed for the cases of the following manoeuvre and the swerving manoeuvre of motorcycles.

For the scenario of the following manoeuvre as shown in Figure 4.4, it is assumed that the front vehicle (n-1) suddenly decelerates to slow down and the subject motorcycle (n) responds to this urgent situation by applying the brake to avoid a possible crash. The threshold-safety-distance of this scenario is defined as the distance that the subject motorcycle needs for stopping to avoid a possible crash with the front vehicle. This distance may be calculated as:

$$D_{TSD}^{FM} = v_n \tau_n + \frac{v_n^2}{2a_n} - \frac{v_{n-1}^2}{2a_{n-1}}$$

(Equation 4.9)

where, D_{TSD}^{FM} is the threshold-safety-distance for the following manoeuvre scenario; τ_n, v_n and a_n are the reaction time, initial speed and braking deceleration of the subject motorcycle respectively; v_{n-1} and a_{n-1} are initial speed and braking deceleration of the front vehicle respectively.

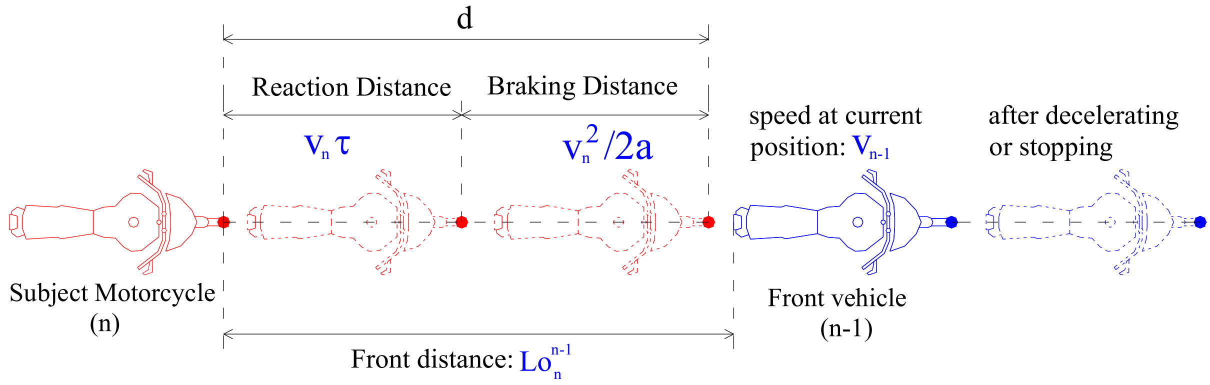


Figure 4.4. Following manoeuvre scenario

With regard to the swerving manoeuvre scenario, it is assumed that the trajectory of the subject motorcycle (n) is the hypotenuse of a right triangle as illustrated in Figure 4.5 and the laterally-following vehicle (m) starts braking while the subject motorcycle starts swerving. The threshold-safety-distance of this movement scenario is defined as the distance that the vehicle (m) needs for stopping to avoid a possible crash while the motorcycle (n) is executing a swerving manoeuvre. This distance is formulated as:

$$D_{TSD}^{SM} = v_m \tau_m + \frac{v_m^2}{2a_m} - \frac{La_n^m \times cos\alpha_n}{sin\alpha_n}$$

(Equation 4.10)

where, D_{TSD}^{SM} is the threshold-safety-distance for swerving manoeuvre scenario; τ_m, v_m and a_m are the reaction time, initial speed and braking deceleration of vehicle (m) respectively, La_n^m is the initial lateral gap between motorcycle (n) and vehicle (m), and α_n is the swerving angle of motorcycle (n).

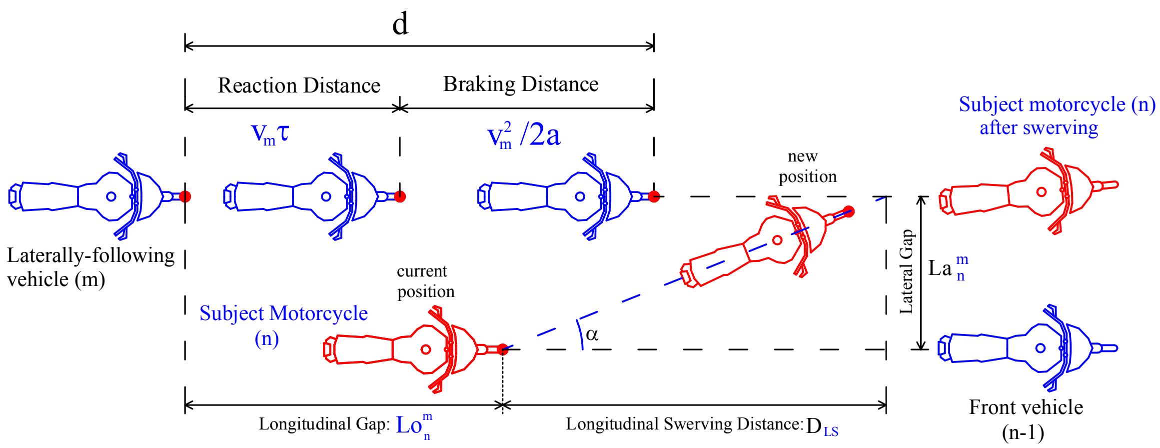


Figure 4.5. Swerving manoeuvre scenario

Step B: Model formulation development

This study defines the conflict as a condition of two consecutively moving motorcycles having inadequate threshold-safety-distance (TSD) such that the following motorcycle will crash into the front motorcycle when it swerves or make an unexpected stop. In the traffic stream, the motorcyclist may choose to follow the front vehicle or to swerve to overtake the front vehicle. When the subject motorcycle follows the front vehicle, a rear-end conflict may occur if it maintains a front distance (Lo_n^{n-1}) less than the D_{TSD}^{FM}. For this assumption, the probability that a following manoeuvre event involves in a rear-end conflict is determined by:

$$Pr(C_n^{n-1}|D_{TSD}^{FM}) = \begin{cases} 1 & if \quad Lo_n^{n-1} \leq D_{TSD}^{FM} \\ 0 & if \quad Lo_n^{n-1} > D_{TSD}^{FM} \end{cases}$$

(Equation 4.11)

Similarly, a sideswipe conflict may occur when the subject motorcycle performs a swerving manoeuvre and the longitudinal gap (Lo_n^m) with the laterally-following vehicle is less than the

D_{TSD}^{SM}. For this assumption, the probability that a swerving manoeuvre event involves in a sideswipe conflict is determined by:

$$Pr(C_n^m | D_{TSD}^{SM}) = \begin{cases} 1 & if \quad L_n^m \leq D_{TSD}^{SM} \\ 0 & if \quad L_n^m > D_{TSD}^{SM} \end{cases}$$

(Equation 4.12)

Equation (4.11) and (4.12) are focused only on one specific interaction between a subject motorcycle with a front vehicle and with a laterally-following vehicle at a given time on a road segment. To estimate the average conflict occurrence frequency on a road segment in a specific time period, a distribution probability function may be applied. In the real traffic, the front distances and the longitudinal gaps have been determined to follow a lognormal distribution (Minh, 2007; Lee, 2009). Therefore, in order to estimate the probability of conflicts occurring for a road segment, the lognormal distribution function was used in this study.

It is assumed that when a random variable Z ($0 < Z < \infty$) follows a lognormal distribution with mean μ and standard deviation σ, the probability that variable Z is less than the value of z is given by (Aitchison and Brown, 1957):

$$\Pr(Z \leq z) = \Phi\left[\frac{ln(z) - \mu}{\sigma}\right]$$

(Equation 4.13)

where, $\Phi[\cdot]$ is the cumulative standard normal distribution

From this theory and under the assumption that the front distances (Lo_n^{n-1}) follow a lognormal distribution with mean $\mu^{Lo_n^{n-1}}$ and standard deviation $\sigma^{Lo_n^{n-1}}$, the probability that a rear-end conflict occurs when the motorcycle follows the front vehicle is given by:

$$Pr(C_n^{n-1}|D_{TSD}^{FM}) = Pr\,(Lo_n^{n-1} \leq D_{TSD}^{F}) = \quad \Phi\left[\frac{ln(D_{TSD}^{FM}) - \mu^{\,Lo_n^{n-1}}}{\sigma^{Lo_n^{n-1}}}\right]$$

(Equation 4.14)

where, $\Phi[\cdot]$ denotes the cumulative standard normal distribution, D_{TSD}^{FM} is the threshold-safety-distance for following manoeuvre scenario as presented in Equation (4.9).

Similarly, under the assumption that the longitudinal gaps (Lo_n^m) follow a lognormal distribution with mean $\mu^{Lo_n^m}$ and standard deviation $\sigma^{Lo_n^m}$, the probability that a sideswipe conflict occurs when the motorcycle swerves to change its current direction is given by:

$$Pr(C_n^m|D_{TSD}^{SM}) = \Pr\,(Lo_n^m \leq D_{TSD}^{SM}) = \quad \Phi\left[\frac{\ln(D_{TSD}^{SM}) - \mu^{\,Lo_n^m}}{\sigma^{Lo_n^m}}\right]$$

(Equation 4.15)

where, $\Phi[\cdot]$ denotes the cumulative standard normal distribution, D_{TSD}^{SM} is the threshold-safety-distance for swerving manoeuvre scenario as presented in Equation (4.10).

4.5. Summary

In this study, to develop crash risk models for motorcycles, crash risk is defined as the result of a series of traffic events which are assumed to be independent. Therefore, the crash risk models are determined by multiplying the probabilities of these events. The crash risk models developed in this work are summarised in Table 4.1.

Table 4.1. Summary of developed models

Models	Following manoeuvre scenario	Swerving manoeuvre scenario
Manoeuvre Choice Models	Following manoeuvre choice $Pr(FM_n\|X)$ (Equation 4.7)	Swerving manoeuvre choice $Pr(SM_n\|X)$ (Equation 4.6)
Threshold-Safety-Distance Indicators (TSD)	TSD indicator for following manoeuvre scenario D_{TSD}^{FM} (Equation 4.9)	TSD indicator for swerving manoeuvre scenario D_{TSD}^{SM} (Equation 4.10)
Conflict Occurrence Models	Rear-end conflict occurrence $Pr(C_n^{n-1}\|D_{TSD}^{FM})$ (Equation 4.14)	Sideswipe conflict occurrence $Pr(C_n^m\|D_{TSD}^{SM})$ (Equation 4.15)
Crash Risk Models	Rear-end crash risk $Pr(RE_{n-1}^n) = Pr\,(FM_n\|X) \times Pr\,(FM_{n-1}\|X) \times Pr\,(C_n^{n-1}\|D_{TSD}^{FM})$ (Equation 4.1)	Sideswipe crash risk $Pr(SW_n^m) = Pr\,(SM_n\|X) \times Pr\,(FM_m\|X) \times Pr\,(C_n^m\|D_{TSD}^{SM})$ (Equation 4.2)

4.6. Conclusions

In this chapter, the modelling process for both rear-end and sideswipe crash risks for motorcyclists in a motorcycle-dominated traffic environment was presented. The potential of each crash type is identified by the joint probability of the motorcyclists' manoeuvre choice and that of conflicts to occur. The manoeuvre choice model was developed based on the discrete choice analysis method using the logistic regression model. For the probabilities of conflicts to occur, the lognormal distribution function was used and based on the concept of the threshold-safety-distance.

CHAPTER 5

DATA COLLECTION

This chapter presents the data collection methodology of this research. The chapter is organised in five main sections. The first section describes the data requirements for the process of model definition. The second section discusses two main methods used to collect the trajectory of vehicles. The third section presents the method selected to collect the data and then the method used to extract the data for this research is shown in section four. The statistical properties of two data sets collected on two road segments from two different Streets in the city of Danang in Vietnam are summarised in the final section.

5.1. Data Requirements

Based on the generic model definitions shown in Chapter 4, the variables included in the proposed models and the associated data required for the model definition are follows:

- Speeds: include the speed of the subject motorcycles, the front vehicles and laterally-following vehicles.
- Relative distances: include the front distances between the subject motorcycles and the front vehicles, the longitudinal and the lateral gaps between the subject motorcycles and the laterally-following vehicles, and the lateral clearances between the front vehicles.

- Road attributes: include the number of lanes, the lane width, the road surface condition and the road grade. The traffic density depends on the number of lanes and lane width and therefore these attributes were collected to investigate the effect of traffic density on crash risk (Equations 4.14, 4.15, 6.11 and 6.12). The braking deceleration and stopping distance of motorcycles depend on the road surface condition (surface friction) and road grade and therefore they also affect crash risk (Equations 4.9 and 4.10).
- Traffic observations: include the following manoeuvre, the swerving manoeuvre, the rear-end conflicts and the sideswipe conflicts.
- Traffic data: include the number of vehicles passed the traffic survey area.

5.2. Data Collection Methods

The required data described above can be obtained from the vehicle trajectories collected in the field. Vehicle trajectories are the observations of the positions of vehicles at discrete points in time. Trajectory data points are spaced in time with short time intervals between them, typically 1 second or less (Toledo, 2003). Speeds, accelerations and decelerations of vehicles are extracted from the time series of the positions of vehicles. Other variables such as relative distances between vehicles, front distances, lateral clearances, lateral gaps and longitudinal gaps may be inferred from the trajectory data.

There are two main methods for collecting the vehicle trajectory data: the video recording method and the floating-car method (Lee, 2007). The former is based on the use of video cameras to record the traffic stream and the latter is based on sensors that are installed on instrumented vehicles to capture the motion and interaction information of those instrumented vehicles.

The major advantages of using the video recordings are that it is low cost and the trajectories of all vehicles in the traffic stream are captured. In addition, this is a naturalistic observation method that is not affected by the observers and researchers, and a video file can be reviewed repeatedly to ensure the quality of information extracted. The main disadvantage of this method is that it is extremely time-consuming to extract vehicles' trajectories from a video file. For example, to extract vehicles' trajectories from an hour's video file, it requires approximately 200 person-hours to process (Lee, 2007).

The advantages of the floating-car method are that the data extraction process is simpler than that of video recording method because the required information is directly obtained from sensors, and a instrumented vehicle can accommodate a wide range of sensors, including video recorders, to collect all required data. However, the main drawback is that this method can only capture the information of the instrumented vehicles and the number of parameters collected depends on the type and number of sensors installed on the instrumented vehicles because each sensor can only collect a specific type of information. Therefore, to obtain all required data, the instrumented vehicles need to be installed with a wide range of sensors which would make the cost of data collection very expensive. Another drawback of this method is that the behaviour of drivers may be affected under surveillance and therefore the information collected may be not naturalistic (Minh, 2007; Lee, 2007; Gue *et al.*, 2010).

5.3. Data Collection Methodology for this Research

As the video recording method can capture all the required information at low cost, this method was chosen.

5.3.1 Video recording equipment selection

A Sony HDR PJ-670 Handycam Camcorder was used to collect data for this research. This video camera was used for recording the traffic stream for several reasons. First, the device is capable of recording image video files with a high resolution of 1280 x 720 pixels and therefore the trajectories of vehicles may be extracted from these video files with high accuracy. Second, it has a large focal length ranged from 32.8 mm to 984.0 mm and thus allows the capture of a wide traffic survey area. In addition, the price of this camcorder is affordable and commensurate for use in this research.

5.3.2 Data collection locations

This research was funded by the Government of Vietnam with the requirement to focus on the country of Vietnam. Therefore, the city of Danang in Vietnam was chosen for conducting the traffic surveys to collect data for this research. Danang is a major city of Vietnam where motorcycles constitute over 80% of total urban traffic and motorcycle crashes account for nearly 70% of the total road crashes. Therefore, it is a good representative of a motorcycle-dominated traffic environment such as those found in South and South East Asia (see Chapter 2). The selected road segments for conducting traffic surveys were chosen in such a manner so that the following criteria could be satisfied:

- The traffic volumes should be large enough in order to be capable of capturing the movement behaviour of the subject motorcycles and their interactions between the subject motorcycles with other influential vehicles.
- There should be no bus stops, parking lots and intersections near the sites in order to capture discrete movements of vehicles and to avoid behaviour of road users affected by these road features.

- There should be normal driving conditions with clear weather, a dry pavement, low wind and un-congested traffic flows.

Consequently, two representative road segments one on Nguyen Van Linh Street and another on Nguyen Tri Phuong Street were chosen to collect data for the models. Moreover, eight additional road segments were also surveyed to supplement the various tests conducted, including: Dien Bien Phu Street, Bach Dang Street, Cach Mang T-8 Street, Nguyen Huu Tho Street, Duong 2-9 Street, Nguyen Tat Thanh Street, Ton Duc Thang Street and Truong Chinh Street. This section only describes the data collection process of the two representative road segments on Nguyen Van Linh Street and Nguyen Tri Phuong Street. The data collected from those eight road segments are shown in Appendix F.

5.3.3 Data collection time

The traffic surveys were conducted on 21 and 22 August 2014, from 6:00 am to 9:00 am and 3:00 pm to 6:00 pm (peak slots: 7:00-8:00 am, and 4:30-5:30 pm). These were clear weather days and thus provided good conditions for capturing the traffic streams by a video camera. As a result, 6 hours of traffic survey was recorded at each site. The selection of these time periods for data collection is justified by several reasons. First, these times are capable of capturing fully the movement characteristics of motorcycles and their interactions during peak hours and non-peak hours of a day. Second, the sample size obtained from 6 hours of traffic observation is large enough to produce a reliable result in statistical analysis process (Peduzzi *el al.*, 1996; Toledo, 2003; Minh, 2007; Lee, 2007; Long, 2012; Shiomi *et al.*, 2013). The trajectories of vehicles were observed at discrete points in time with intervals of 0.5 second and each vehicle was observed from 3.0 to 5.0 seconds, therefore the collected data were likely to capture a wide range of traffic conditions (e.g. various traffic density conditions) and a large number of vehicle trajectories can be obtained from 6 hours of traffic observation. In addition, these are clear and bright times of a day that provide good visibility for obtaining high quality video images.

5.3.4 Characteristics of road segment on Nguyen Van Linh Street

A road segment of length 35.0 m and of width 8.0 m on Nguyen Van Linh Street was the first site for the traffic survey. This road has two lanes and the width of each lane is 4.0 m. The grade of this segment is 0.0 per cent, and the road surface was in good condition. The characteristics of this road segment are shown in Figure 5.1.

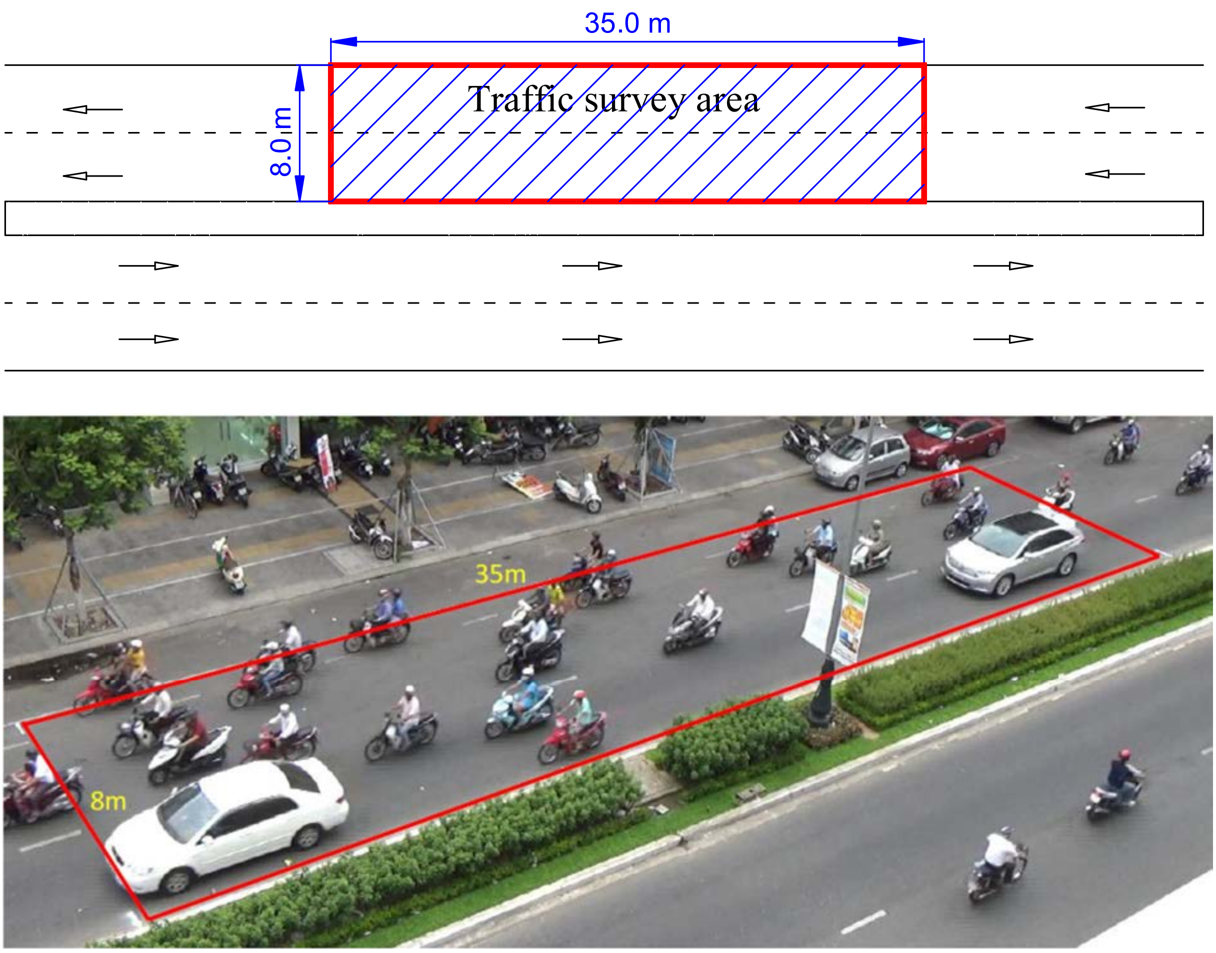
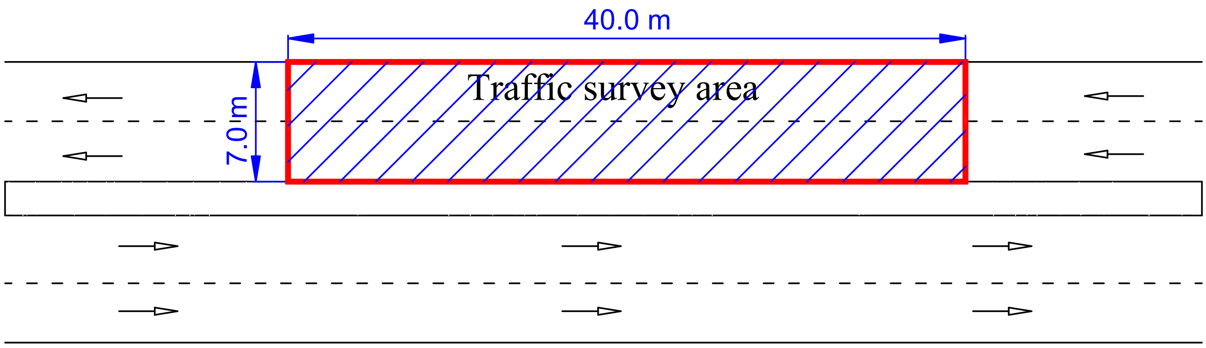


Figure 5.1. The road segment on Nguyen Van Linh Street

5.3.5 Characteristics of road segment on Nguyen Tri Phuong Street

A segment of length 40.0 m and of width 7.0 m on Nguyen Tri Phuong Street was the second site for the traffic survey. This road has two lanes and the width of each lane is 3.5 m. The grade of this segment is 0.0 per cent, and the road surface is in good condition. The characteristics of this road segment are shown in Figure 5.2.



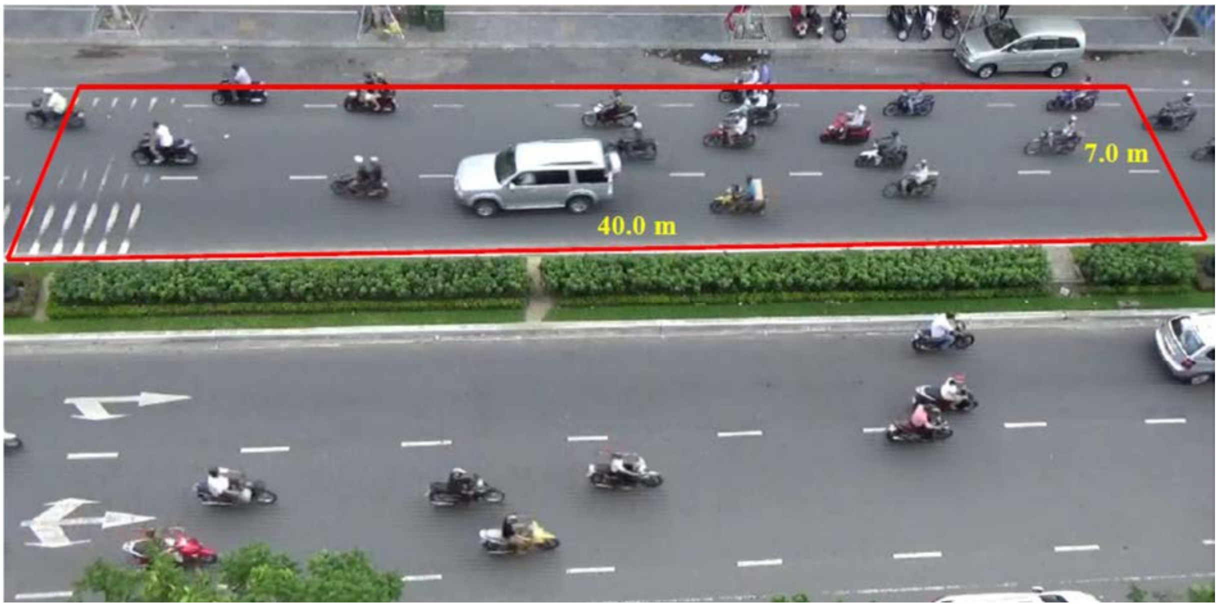


Figure 5.2. The road segment on Nguyen Tri Phuong street

5.4. Data Extraction

The trajectories of the vehicles were extracted from the recorded video files using the SEV (Speed Estimation from Video Data) computer software which converts video screen coordinates into roadway coordinates. This computer programme was developed by Minh (2007) and it is free to use. The software displays a video file on screen and the users are capable of tracking the trajectories of the target vehicles by clicking the mouse on the positions of front central point of these vehicles on screen. The coordinates of the positions of target vehicles in the video image were obtained by mouse clicks then converted into roadway coordinates and recorded into a database in Excel file format. The trajectory data of all vehicles in the sections considered and the speeds derived from these trajectories were used to generate the required variables included in the developed models. The conflict events were observed in the field via the video recordings (Parker and Zegeer, 1989).

5.5. Data Sets Statistics

5.5.1 Statistical properties of dataset from Nguyen Van Linh street

The data set of this road segment contains 535 observations of the trajectories of 108 subject motorcycles and 2140 observations of 432 influential vehicles. The trajectory data of vehicles and the speeds derived from these trajectories were used to generate the required variables. Table 5.1 summarises the statistics of the variables included in the proposed models. The data shows that the speeds of subject motorcycles range from 4.68 m/sec to 12.51 m/sec, with a mean of 9.68 m/sec while that of the front vehicles range from 4.07 m/sec to 10.88 m/sec with a mean of 7.04 m/sec. The front distances vary from 0.97 m to 5.58 m with a mean of 2.08 m. The longitudinal gaps range from 1.21 to 7.18 m with a mean of 2.96 m and the lateral gaps range from 0.53m to 4.02 m with a mean of 1.48 m. This dataset is presented in Appendix G.

Table 5.1. Statistics of data set on Nguyen Van Linh Street

Variables	Mean	Std	Minimum	Maximum
Speed of subject motorcycles (m/s)	9.68	1.32	4.68	12.51
Speed of front motorcycles (m/s)	7.04	1.10	4.07	10.88
Relative speeds (m/s)	1.19	1.01	-1.09	4.11
Front distances (m)	2.08	1.20	0.97	5.58
Longitudinal gaps (m)	2.96	1.22	1.21	7.18
Lateral gaps (m)	1.48	0.65	0.53	4.02
Lateral clearance (m)	1.62	0.76	0.70	3.88

5.5.2 Statistical properties of dataset from Nguyen Tri Phuong Street

The data set in this road segment comprises 461 observations of the trajectories of 95 subject motorcycles and 1844 observations of 368 influential vehicles. The statistics of variables included in the proposed model are summarised in Tables 5.2. For this road, the speeds of subject motorcycles range from 4.58 m/sec to 12.06 m/sec with a mean of 9.48 m/sec while the mean of speed of front vehicles is 7.43 m/sec. The mean of front distances is 2.42 m and they range from 1.05 m to 5.31 m. The longitudinal gaps range from 1.82 to 6.63 m with a mean of 3.15 m and the lateral gaps range from 0.5 to 3.48 m with a mean of 1.43 m. This dataset is presented in Appendix E.

Table 5.2. Statistics of data set on Nguyen Tri Phuong Street

Variables	Mean	Std	Minimum	Maximum
Speed of subject motorcycles (m/s)	9.48	1.29	4.58	12.06
Speed of front motorcycles (m/s)	7.43	1.21	4.35	10.74

Relative speeds (m/s)	0.86	0.97	-2.24	3.67
Front distances (m)	2.42	1.27	1.05	5.31
Longitudinal gaps (m)	3.15	1.19	1.82	6.63
Lateral gaps (m)	1.43	0.67	0.50	3.48
Lateral clearance (m)	1.79	0.86	0.79	3.82

These two datasets were used to fit the model developed in this research. It should be appreciated that a more comprehensive dataset comprising road segments different from the above and preferably collected from other cities or countries with similar traffic characteristics would be required for the model fitting purpose with a wider application. However, such a task was beyond the scope of this study, which sought to demonstrate the development process of the model and its testing, and would require significant resources which were not available during this PhD programme.

5.6. Summary

In this chapter, the methodology of data collection for this research was presented. The video recording method was used to record the traffic data on road segments in the city of Danang in Vietnam. It was felt that the locations selected to collect data could be a good representative of a motorcycle-dominated traffic environment considered in this study and the data collected to use for the purpose of model specification and validation could satisfy an empirically driven sampling process within the resource constraints of this study.

CHAPTER 6

MODEL FITTING

This chapter presents the process of fitting the models developed in Chapter 4. The model fitting is the process of using the real data collected in the field (see Chapter 5) to estimate the unknown coefficients of the independent variables and to select independent variables either for inclusion or exclusion from the proposed models that are only found to be significant in explaining the outcome variable. The fitting process of the proposed crash risk models are conducted for the two components included in these model formulations. The first component is the manoeuvre choice model capturing the manoeuvre behaviour of the motorcyclist and the second component is the conflict occurrence models capturing the probability of conflicts.

This chapter is organised in two main sections. The first section describes the process of fitting the manoeuvre choice model and the second section presents the process of specifying the conflict occurrence models.

6.1. Manoeuvre Choice Model

6.1.1 Methodology

The process of fitting the manoeuvre choice model was conducted in the following two steps (A and B).

Step A: Estimating the coefficients of independent variables

This step presents the process to fit the logistic regression model by using the real traffic data. Suppose there is a sample of n independent observations of the pair (x_i, y_i), i = 1, 2, …, n, where y_i is the value of a binary outcome variable representing the choice of the subject motorcycle to perform either a swerving or following manoeuvre, and x_i is the value of the independent variable explaining the manoeuvre choice for the subject motorcycle i^{th}. To fit the logistic regression model of Equation (4.5) to a set of data collected in the field requires that the values of unknown coefficients $\beta = (\beta_0, \beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6, \beta_7)$ are estimated.

The method used to estimate the unknown coefficients of the linear regression model is that of the least squares. For this method, the values of coefficients that minimise the sum of squared deviations of the observed values of outcome variables from the predicted values are chosen. The method that leads to the least squares function is called maximum likelihood and this approach is used to estimate the unknown coefficients of the logistic regression model (Hosmer and Lemeshow, 1989). For the maximum likelihood method, the likelihood function expressing the probability of the observed data as a function of unknown coefficients is built. The maximum likelihood estimators of these coefficients are chosen to those values which maximise the likelihood function. A brief review of fitting the logistic regression model is given below. Further details may be found elsewhere (Hosmer and Lemeshow, 1989).

If the outcome variable Y is coded as 1 or zero representing the choice of the swerving or following manoeuvre of the subject motorcycle respectively, the expression $\pi(x) = P(Y=1|x)$ provides the conditional probability that Y is equal to 1 given x. It follows that the quantity $1 - \pi(x)$ gives the conditional probability that Y is equal to zero given x, $P(Y=0|x)$. Thus, for those pairs (x_i, y_i) where y_i=1, the contribution to the likelihood function is $\pi(x_i)$, and for those pairs where y_i=0, the contribution to the likelihood function is 1 − $\pi(x_i)$, where the quantity $\pi(x_i)$ denotes the values of $\pi(x_i)$ computed at x_i. A convenient way to express the contribution to the likelihood function for the pair (x_i, y_i) is through the term (Hosmer and Lemeshow, 1989):

$$\xi(x_i) = \pi(x_i)^{y_i}[1 - \pi(x_i)]^{1-y_i}$$

(Equation 6.1)

Since the observations are assumed to be independent, the likelihood function is given by:

$$l(\beta) = \prod_{i=1}^{n} \xi\,(x_i)$$

(Equation 6.2)

It is easier mathematically to work with the log of Equation (6.2), thus this function is rewritten by the log-likelihood as follow:

$$L(\beta) = \ln[l(\beta)] = \sum_{i=1}^{n}\{y_i \ln[\pi(x_i)] + (1 - \ y_i)ln[1 - \pi(x_i)]\}$$

(Equation 6.3)

To find the value of *β,* the log-likelihood function *L(β)* is maximised by differentiating this function with respect to *β* and setting the resulting expressions equal to zero. These likelihood equations are as follows (Hosmer and Lemeshow, 1989):

$$\sum_{i=1}^{n}[y_i - \pi\,(x_i)] = 0$$

$$\sum_{i=1}^{n} x_i[y_i - \pi\,(x_i)] = 0$$

(Equation 6.4)

The value of β given by the solution to Equations (6.4) is called the maximum likelihood estimate.

Step B: Assessing the significance of independent variables (Hosmer and Lemeshow, 1989)

To obtain the best fitting model, the significance of independent variables included in the model is assessed after the coefficients estimated. This step involves in testing a statistical hypothesis to determine whether the independent variables included in the model are significantly related to the outcome variable. This process is carried out by comparing observed values of the response variable to predicted values obtained from models with and without the variable in question. The comparison of the observed to predicted values using the log likelihood function in Equation (6.3) is based on the likelihood ratio expressed as follows:

$$D = -2\,ln\left[\frac{(likelihood\ of\ the\ current\ model)}{(likelihood\ of\ the\ saturated\ model)}\right]$$

(Equation 6.5)

In Equation (6.5), the saturation model is one that contains as many parameters as there are data points, and the current model is one that contains only the variable under question. Using Equation (6.3), Equation (6.5) becomes:

$$D = -2\sum_{i=1}^{n}\left[y_i ln\left(\frac{\hat{\pi}_i}{y_i}\right) + (1-y_i)ln\left(\frac{1-\hat{\pi}_i}{1-y_i}\right)\right]$$

(Equation 6.6)

where, $\hat{\pi}_i$ is the maximum likelihood estimate of $\pi(x_i)$

To assess the significance of an independent variable, the value of D should be compared with and without the independent variable in the equation. The change in the value of D due to the inclusion of the independent variable in the model:

$$G = D \text{ (for the model without the variable)} - D \text{ (for the model with the variable)}$$

Because the likelihood of the saturated model is common to both values of D being differenced to compute G, this change can be expressed as:

$$G = -2\ ln\left[\frac{(likelihood\ without\ the\ variable)}{(likelihood\ with\ the\ variable)}\right]$$

(Equation 6.7)

6.1.2 Data description

A data set containing 535 observations of the trajectories of 108 subject motorcycles and 2140 observations of 432 influential vehicles on Nguyen Van Linh Street (Chapter 5) is used to fit the manoeuvre choice model (see Appendix G). Within the resource constraints of this study, it was felt that a data set containing 535 observations used to estimate the unknown coefficients of the logistic regression model could satisfy an empirically driven sampling process. It should be appreciated that enhanced results could be obtained if a more comprehensive data set were used.

6.1.3 Results and discussions

The estimation process was based on the maximum-likelihood algorithm as presented in step A and to simplify the calculation process, a statistic software package, named SPSS, was used in this study. The estimate results for the values of unknown coefficients, β_0, β_1, β_2, β_3, β_4, β_5, β_6, β_7, along with the statistic test are summarised in Table 6.1.

Table 6.1. Estimated coefficients of the manoeuvre choice model

Variables	Coefficients	Estimated Coefficients	Standard Error	Wald test	p-value
$Lo_{\mathrm{n}}^{\mathrm{n-1}}$	β_1	-1.676	0.234	36.364	< 0.001
$V_{\mathrm{n}}^{\mathrm{n-1}}$	β_2	1.452	0.283	18.685	< 0.001
Lo_n^m	β_3	0.139	0.056	48.656	0.013
$V_{\mathrm{n}}^{\mathrm{m}}$	β_4	0.223	0.110	10.564	0.043
La_{n-1}	β_5	1.444	0.193	24.411	< 0.001
Te_{n-1}	β_6	-2.035	1778.123	14.497	0.999
Te_m	β_7	-0.641	0.096	0.000	< 0.001
constant	β_0	2.040	2240.436	0.000	0.999

In this step, along with fitting the model, all the independent variables were first tested on the Wald statistic as defined in Equation (6.7) to determine those variables that are significant and then continue with testing for the significance of variables as presented in step B. The first statistic test for the estimate results of coefficients show that the p-value of Wald test for variable (Te_{n-1}) is 0.999 which is much greater than the desired significance level of 0.05, therefore it is necessary to continue to conduct step B to assess the significance of this variable in explaining the outcome variable.

In step B, for the fitted model whose estimated coefficients are given in Table 6.1, the change in log likelihood along with its p-values were calculated for the independent variables in the model. The statistical results are summarised in Table 6.2. As the results shown, the change in log likelihood for the variable "Te_{n-1}" is rather low, being 0.015, and the p-value of 0.903 is much greater than the desired significance level of 0.05. This statistic demonstrates that this variable is found to be not significant in explaining the outcome variable and therefore this variable should be removed from the model to obtain a reduced model.

Table 6.2. Likelihood ratio test for estimated coefficients

Variables	Estimated Coefficients	Model Log Likelihood	Change in -2 Log Likelihood	Significance of the Change
$Lo_{\mathrm{n}}^{\mathrm{n-1}}$	-1.676	-132.549	95.051	0.000
$V_{\mathrm{n}}^{\mathrm{n-1}}$	1.452	-100.922	31.797	0.000
Lo_n^m	0.139	-88.333	6.618	0.010
$V_{\mathrm{n}}^{\mathrm{m}}$	0.223	-87.087	4.126	0.042
La_{n-1}	1.444	-148.927	127.807	0.000
Te_{n-1}	-2.035	-85.031	0.015	0.903
Te_m	-0.641	-123.541	77.034	0.000

The coefficient of the independent variables include in the reduced model was re-estimated and was tested statistically as summarised in Table 6.3.

Table 6.3. Estimated coefficients for the best fitting manoeuvre choice model

Variables	Estimated Parameters	Standard Error	Wald test	p-value
$Lo_{\mathrm{n}}^{\mathrm{n-1}}$	-1.677	0.234	51.246	< 0.001
$V_{\mathrm{n}}^{\mathrm{n-1}}$	1.452	0.283	26.379	< 0.001
Lo_n^m	0.139	0.056	6.161	0.013
$V_{\mathrm{n}}^{\mathrm{m}}$	0.224	0.109	4.196	0.041
La_{n-1}	1.445	0.193	56.020	< 0.001
Te_m	-0.642	0.096	44.652	< 0.001
constant	-0.524	0.591	0.785	0.376

By considering the Wald statistical tests for coefficients shown in Table 6.3, all p-values of the tests for estimated coefficients are less than the level of significance of 0.05, implying that the model contains those variables that should be in the model and these variables have been entered in the correct functional form. As the results show, the front distance is a significant factor contributing to the decision of motorcyclists in choosing the swerving manoeuvre. The coefficient of this variable is negative, implying that motorcyclists are more likely to swerve to change their current directions if the gaps maintained with the front vehicles become shorter. The difference in speeds between the subject motorcycles and the front vehicles, and the lateral clearance space of the front vehicles are factors found to contribute significantly to the manoeuvre behaviour of motorcyclists. These coefficients are positive, indicating that motorcyclists are more likely to choose swerving manoeuvres with an increase in the values of these factors. The coefficients of the longitudinal gap variable and the difference in speed between the subject motorcycles and the laterally-following vehicles are positive as expected, meaning that the motorcyclists tend to perform the swerving manoeuvre as the values of these factors increased.

Consequently, the logit model with the variables found to be significant contributing to the decision of the motorcyclists in choosing their manoeuvre behaviour is given by:

$$g(x_i) = -0.524 - 1.677 Lo_n^{n-1} + 1.452 V_n^{n-1} + 0.139 Lo_n^{m} + 0.224 V_n^{m} + 1.445 La_{n-1} - 0.642 Te_{m}$$

(Equation 6.8)

As such, the best fitting model capturing the probability that the motorcyclist chooses the swerving manoeuvre is given by:

$$Pr(SM_n|X) = \frac{e^{-0.524-\ 1.677Lo_n^{n-1}+1.452V_n^{n-1}+0.139\ Lo_n^m+0.224\ V_n^m+1.445\ La_{n-1}-0.642Te_m}}{1+e^{-0.524-\ 1.677Lo_n^{n-1}+1.452V_n^{n-1}+0.139Lo_n^m+0.224V_n^m+1.445La_{n-1}-0.642Te_m}}$$

(Equation 6.9)

Therefore, the probability that the motorcyclist chooses the following manoeuvre is:

$$Pr(FM_n|X) = \frac{1}{1+e^{-0.524-\ 1.677Lo_n^{n-1}+1.452V_n^{n-1}+0.139Lo_n^m+0.224V_n^m+1.445La_{n-1}-0.642Te_m}}$$

(Equation 6.10)

6.2. Conflict Occurrence Models

To estimate the mean and standard deviation of the logarithm of the front distance and longitudinal gap as presented in Equation (4.14) and Equation (4.15), a dataset from Nguyen Van Linh Street was used (section 5.1). SPSS statistic software has been used to analyse the statistical properties and the distributions of these variables.

6.2.1 Front distance and longitudinal gap distribution

The statistical properties of the front distance (**Lo_n^{n-1}**) and longitudinal gap (**Lo_n^m**) from the dataset are summarised in Table 6.4 and Figure 6.1. As shown in Figure 6.1, the histograms of these variables have the shape of a lognormal curve. The Kolmogorov–Smirnov test (KS test) measure was applied to verify the assumption of the distribution for the longitudinal gap and front distance and the results illustrate that they follow a lognormal distribution.

Table 6.4. The statistical properties of the front distance and longitudinal gap

Factor	Number of observations	Observation data		Lognormal distribution		K-S test for Lognormal distribution
		Mean	Standard Deviation (SD)	Mean	SD	Confidence level
Front distance	1047	2.08	1.20	1.23	0.52	0.509
Longitudinal gap	792	2.96	1.22	1.29	0.30	0.948

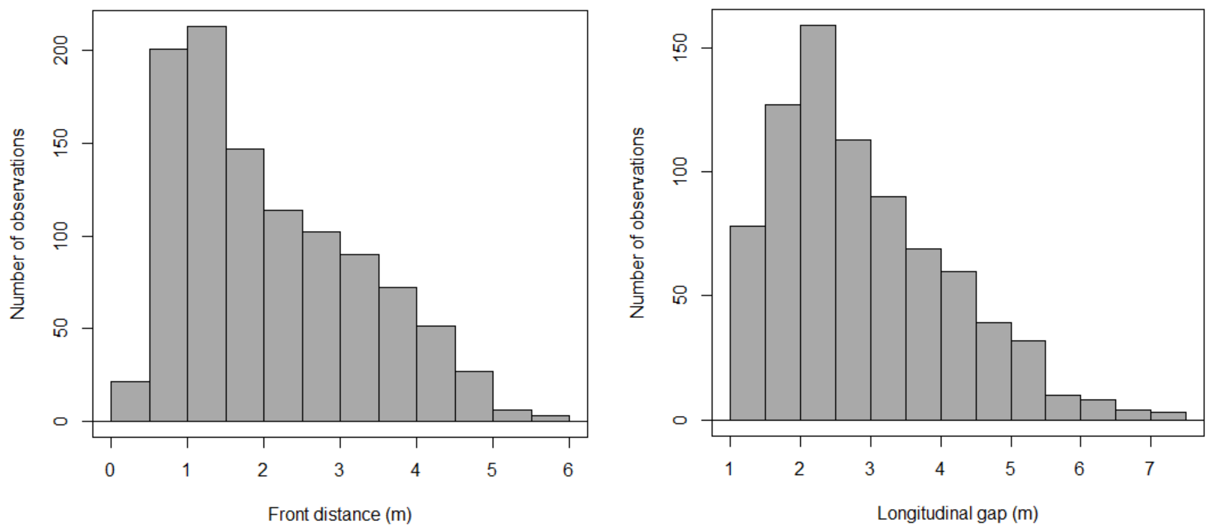


Figure 6.1. Histogram of the front distance and longitudinal gap

6.2.2. Relationship of front distance and longitudinal gap with traffic density

In this research, the traffic density is defined as the number of motorcycles travelling on a road segment of length 100.0 m and width 10.0 m. From the dataset considered, it is found that the traffic density is correlated with the front distance and longitudinal gap and their relations are described in Figure 6.2. To examine their mathematical relationships, a data analysis procedure is conducted by investigating four common regression functions: Linear, Exponential, Polynomial and Power. The results of estimating the coefficients and the statistical test for all candidate functions are shown in Tables 6.5 and 6.6. The statistical tests suggest that the polynomial function form fits well to the observed data, with the highest value of R-squared for both front distance and longitudinal gap, and therefore this function form is selected in this research.

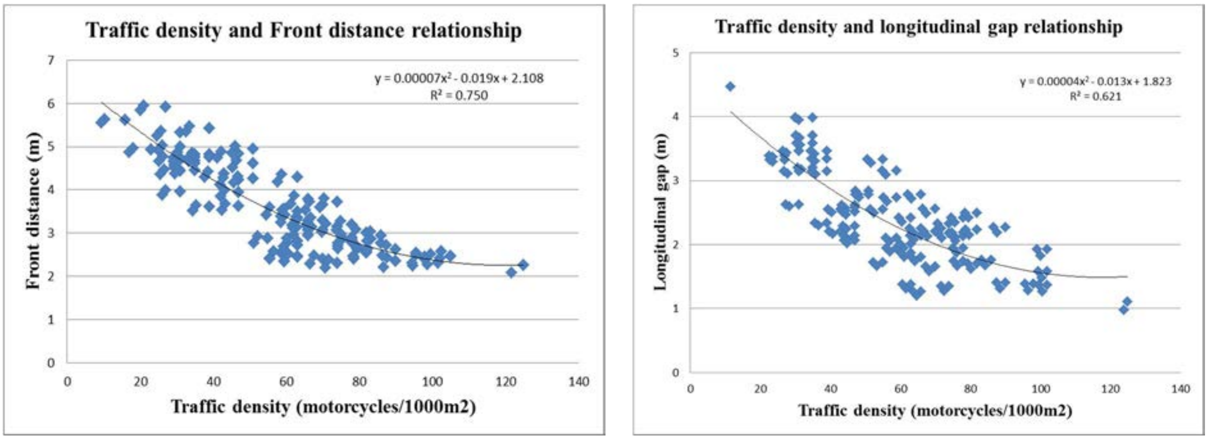


Figure 6.2. The relationship of traffic density with the front distance and longitudinal gap

Table 6.5. The relationship between the front distance and traffic density

Statistical relationship	Equation form	R-squared value
Linear	$\mu_{Lo_n^{n-1}} = \ln(Lo_n^{n-1}) = -0.0101Den + 1.857$	0.722
Exponential	$\mu_{Lo_n^{n-1}} = \ln(Lo_n^{n-1}) = 2.0011e^{-0.008Den}$	0.718
Polynomial	$\boldsymbol{\mu_{Lo_n^{n-1}} = \ln(Lo_n^{n-1}) = 7 * 10^{-5}\, Den^2 - 0.019Den + 2.108}$	**0.750**
Power	$\mu_{Lo_n^{n-1}} = \ln(Lo_n^{n-1}) = 7.5428Den^{-0.454}$	0.707

Table 6.6. The relationship between the longitudinal gap and traffic density

Statistical relationship	Equation form	R-squared value
Linear	$\mu_{Lo_n^m} = \ln(Lo_n^m) = -0.0075Den + 1.6594$	0.603
Exponential	$\mu_{Lo_n^m} = \ln(Lo_n^m) = 1.7433e^{-0.006Den}$	0.596
Polynomial	$\boldsymbol{\mu_{Lo_n^m} = \ln(Lo_n^m) = 4 * 10^{-5}\, Den^2 - 0.013Den + 1.823}$	**0.621**
Power	$\mu_{Lo_n^m} = \ln(Lo_n^m) = 4.9205Den^{-0.352}$	0.592

where, *Den* is the traffic density, $\ln(Lo_n^m)$ is the natural logarithm of the longitudinal gap, $\ln(Lo_n^{n-1})$ is the natural logarithm of the front distance, *e* (≈ 2.71828) is the mathematical constant.

6.2.3 Model specification

Using Equation (4.14), with the parameters of the front distance distribution estimated in Section 6.2.1 and 6.2.2, the probability that a rear-end conflict occurs when the motorcycle follows the front vehicle is given by:

$$Pr(C_n^{n-1}|D_{TSD}^{FM}) = \Phi\left[\frac{ln(D_{TSD}^{FM}) - (7 * 10^{-5}\, Den^2 - 0.019Den + 2.108)}{0.52}\right]$$

(Equation 6.11)

Similarly, using Equation (4.15), the probability that a sideswipe conflict occurs when the motorcycle swerves to change its current direction is given by:

$$Pr(C_n^m|D_{TSD}^{SM}) = \Phi\left[\frac{ln(D_{TSD}^{SM}) - (4 * 10^{-5}\, Den^2 - 0.013Den + 1.823)}{0.3}\right]$$

(Equation 6.12)

6.3. Summary

6.3.1 Rear-end crash risk model

Combining Equations (6.10) and (6.11), the rear-end crash risk model presented in Equation (4.1) becomes:

$$Pr(RE_{n-1}^{n}) = \frac{1}{1+e^{-0.524-1.677Lo_n^{n-1}+1.452V_n^{n-1}+0.139Lo_n^m+0.224V_n^m+1.445La_{n-1}-0.642Te_m}}$$
$$\times \frac{1}{1+e^{-0.524-1.677Lo_n^{n-1}+1.452V_n^{n-1}+0.139Lo_n^m+0.224V_n^m+1.445La_{n-1}-0.642Te_m}}$$
$$\times \Phi\left[\frac{ln(D_{TSD}^{FM})-(7*10^{-5}\ Den^2-0.019Den+2.108)}{0.52}\right]$$

(Equation 6.13)

6.3.2 Sideswipe crash risk model

Combining Equations (6.9), (6.10) and (6.12), the sideswipe crash risk model presented in Equation (4.2) becomes:

$$Pr(SW_n^m) = \frac{e^{-0.524-1.677Lo_n^{n-1}+1.452V_n^{n-1}+0.139Lo_n^m+0.224V_n^m+1.445La_{n-1}-0.642Te_m}}{1+e^{-0.524-1.677Lo_n^{n-1}+1.452V_n^{n-1}+0.139Lo_n^m+0.224V_n^m+1.445La_{n-1}-0.642Te_m}}$$
$$\times \frac{1}{1+e^{-0.524-1.677Lo_n^{n-1}+1.452V_n^{n-1}+0.139Lo_n^m+0.224V_n^m+1.445La_{n-1}-0.642Te_m}}$$
$$\times \Phi\left[\frac{ln(D_{TSD}^{SM})-(4*10^{-5}\ Den^2-0.013Den+1.823)}{0.3}\right]$$

(Equation 6.14)

6.4. Conclusion

In this chapter, the process of fitting the rear-end and sideswipe crash risk models was presented. The dataset collected from Nguyen Van Linh Street was used to estimate the unknown coefficients of the proposed models. The statistical tests were applied to verify the fitting process and the test results illustrated that the developed models fit well to the real data from the dataset considered. The significance of independent variables was also assessed and the statistical tests showed that the independent variables included in the best fitting models were significantly related to the dependent variables.

CHAPTER 7

SENSITIVITY ANALYSIS

This chapter presents the sensitivity analysis of the rear-end and sideswipe crash risk models developed in this study. The main purpose of this task is to capture the effect of input variables on the outputs of the proposed models. This sensitivity analysis serves to supplement the field validation procedure and to assist in developing countermeasures to reduce the crash risk for motorcyclists.

This chapter is organised in three main sections. The first section presents the methodology used to investigate the effect of independent variables included in the developed models on the crash potentials. The second section describes the dataset used for this task. The final section shows the contribution of these variables on the potential of both rear-end and sideswipe crashes for motorcycles.

7.1. Methodology

As stated in Chapter 4, this study defines the crash risk as the probability of conflict occurring that potentially results in crash event if the two consecutive motorcycles involved in the conflict do not take any evasive action to avoid the occurrence of a crash. Therefore, to investigate the effect of risk factors contributing to the crash risk, their influence on the probabilities of conflicts are examined using the developed models presented in Equations (6.13) and (6.14). The changes in the input variables may lead to the changes in the outputs of the proposed models, meaning that the crash risk may change correspondingly to the values of input factors. Consequently, the effect of contributing factors included in the proposed models on the crash risk for motorcyclists are investigated as follows:

a. *Front distance variable*
b. *Speed difference variable*
c. *Longitudinal gap variable*
d. *Lateral clearance variable*
e. *Speed variable*
f. *Traffic density variable*

The methodology used to investigate the effect of a variable on crash risk is based on the changes of outputs due to the change in values of that variable while the values of other variables are kept unchanged. The range of input values for an investigated variable is based on the minimum and maximum values determined from the real data collected in the field. The unchanged values of other variables inputted in the models are the means estimated from the data set considered. Understanding the effect of contributing factors on crash risk, means that countermeasures may be subsequently developed to reduce the crash potential.

7.2. Data Description

The data set from Nguyen Tri Phuong Street was used for this task (Chapter 5). The statistics of input variables used to estimate the potential of crashes are summarised in Table 5.18. To simplify the calculation process, several input variables such as reaction time of motorcyclists, braking deceleration of motorcycles and swerving angle of motorcycles are assumed to be a constant. Specifically, the reaction time (τ) of the motorcyclists is 0.52 second (Minh, 2007), the braking deceleration of motorcycles in emergency situation is 6.02

m/s^2 and that for dry and wet surface conditions are 4.59 m/s^2 and 3.66 m/s^2 respectively (Davoodi and Hamid, 2013), the swerving angle is 12.5 degrees (the mean estimated from the data set considered).

Table 7.1. Summary of the data set for sensitivity analysis

Variables	Mean	Std	Minimum	Maximum
Speed of subject motorcycles (m/s)	9.48	1.29	4.58	12.06
Speed difference (m/s)	0.86	0.97	-2.24	3.67
Front distances (m)	2.42	1.27	1.05	5.31
Longitudinal gaps (m)	3.15	1.19	1.82	6.63
Lateral clearance (m)	1.79	0.86	0.79	3.82

7.3. Result and Discussions

7.3.1 The effect of the front distance variable on crash potentials

To investigate the influence of the front distance variable on crash potentials, the different values of this factor ranging from 1.0 m to 5.0 m were used to input in the proposed models to obtain the outputs. The probabilities of conflicts occurring derived by those values are shown in Table 7.2. These probability results represent the potential of a crash due to the changes of front distance variable. The trend of this change is shown in Figure 7.1. It can be seen from the results that the rear-end crash potential increases as the front distance increases and reaches a peak at the value of 3.0 m and then decreases onwards while the sideswipe crash risk decreases as the values of front distance increase. This may be explained that when the front distance is long, motorcyclists are more likely to choose to follow the front vehicles and this leads to an increase in the rear-end crash potential and a decrease in sideswipe crash potential. Rear-end crashes are likely to occur if the front distance is less than 3.0 m because those of values are less than the threshold safety distance needed for the motorcyclists to take proper evasive actions to avoid the rear-end crash. The outputs also illustrate that the total risk of crashes increases significantly if the front distance factor is less than 2.5 m. This may be due to that when the front distance is less than 2.5 m, the rear-end crash risk increases significantly while the sideswipe risk decreases insignificantly and therefore the total risk will increase correspondingly. The results found in this investigation may be used as a guidance to develop safety treatment measures to reduce the occurrence of crash potential affected by this contributing factor.

Table 7.2. The effect of the front distance factor on crash risk

Front distance (m)	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
Rear-end crash risk	0.025	0.043	0.064	0.082	0.089	0.081	0.064	0.045	0.030
Sideswipe crash risk	0.134	0.129	0.119	0.101	0.075	0.047	0.025	0.012	0.006
Total crash risk	0.16	0.17	0.18	0.18	0.16	0.13	0.09	0.06	0.04

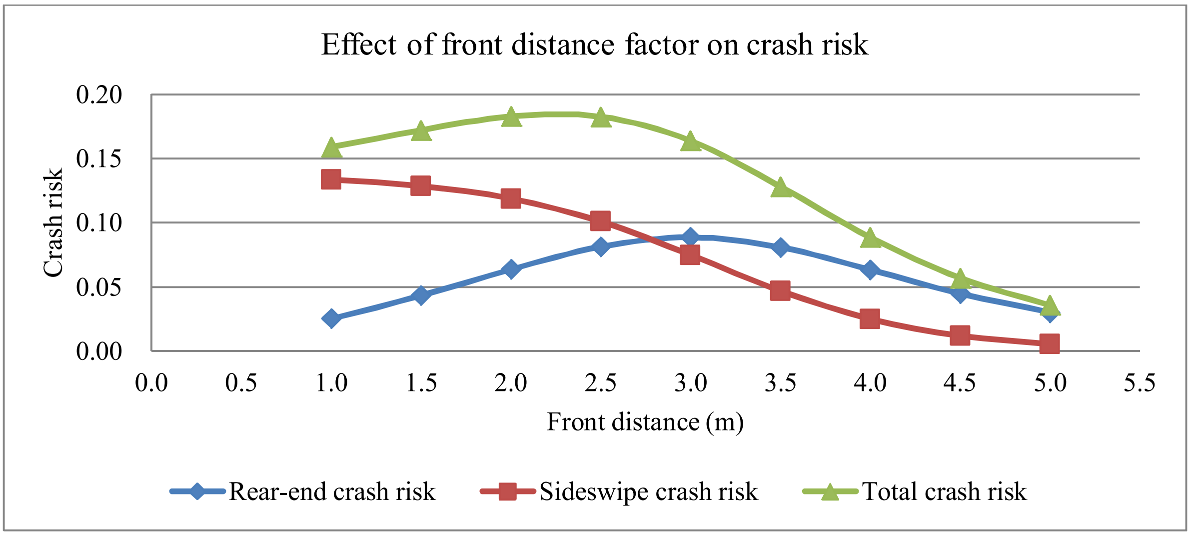


Figure 7.1. The effect of the front distance factor on crash risk

7.3.2 The effect of the speed difference variable on crash potential

The effect of the difference in speed between the subject motorcycle and the front vehicles is investigated by evaluating the change in crash potential output due to the change in the values of this factor. Table 7.3 shows the results estimated for different values ranged from -7.5 km/h to 15.0 km/h for the speed difference factor and the tendencies of those changes are illustrated in Figure 7.2. As shown in the results, the potential of rear-end and sideswipe crashes approach to zero when the differences in their speeds are less than -5.0 km/h. Although the speed of the subject motorcycle is slower than that of the front vehicle (from -5.0 km/h to zero), the probabilities of rear-end crash potential are still different form zero. This may be explained by the scenario as follows: i) the subject motorcycle follows the front vehicle when the speed of the front vehicle is higher than that of the subject motorcycle, ii) the front vehicle suddenly slows down when an emergency situation ahead occurs, iii) the subject motorcycle must apply a brake to avoid a possible rear-end crash with the front vehicle, iv) because the subject motorcycle maintains a short distance with the front vehicle and this distance is less than the distance needed for the subject motorcycle to apply a brake to avoid a rear-end crash with the front vehicle and therefore a rear-end crash may occur. It may also be seen the rear-end crash risk decreases from the value of 2.5 km/h onwards and the sideswipe crash risk increases significantly from that value. This may be due to that motorcyclists are more likely to change their current directions to overtake the front vehicles instead of choosing the following manoeuvre. The outputs also show the total risk of crashes is significant when the speed difference values ranged from 2.5 km/h to 7.5 km/h.

Table 7.3. The effect of differential speed on crash risk

Speed difference (km/h)	-7.5	-5.0	-2.5	0.0	2.5	5.0	7.5	10.0	12.5	15.0
Rear-end crash risk	0.000	0.009	0.051	0.093	0.109	0.089	0.053	0.026	0.020	0.015
Sideswipe crash risk	0.001	0.003	0.008	0.020	0.044	0.077	0.107	0.125	0.128	0.131
Total crash risk	0.00	0.01	0.06	0.11	0.15	0.17	0.16	0.15	0.15	0.15

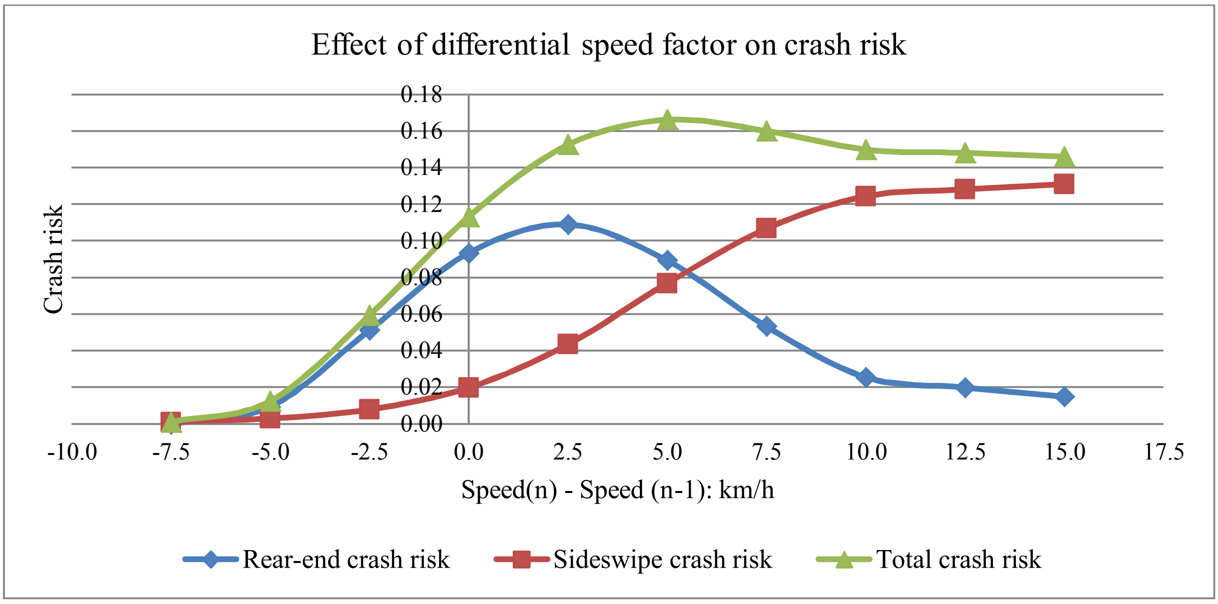


Figure 7.2. The effect of speed difference factor on crash risk

7.3.3 The effect of the longitudinal gap variable on crash potential

The influence of the longitudinal gap factor on the crash potentials is examined by estimating the crash risk for different values of this factor ranged from 0.5 m to 4.5 m. The estimate results are described in Table 7.4 and Figure 7.3. It may be seen from the results that the crash risk decreases with the higher value of this factor. As may also be seen, the potential of sideswipe crash approaches to zero from the values of 3.5 m onwards.

Table 7.4. The effect of longitudinal gap on crash risk

Longitudinal gap (m)	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5
Rear-end crash risk	0.103	0.099	0.096	0.092	0.089	0.085	0.082	0.078	0.075
Sideswipe crash risk	0.495	0.498	0.377	0.188	0.071	0.023	0.007	0.002	0.001
Total crash risk	0.60	0.60	0.47	0.28	0.16	0.11	0.09	0.08	0.08

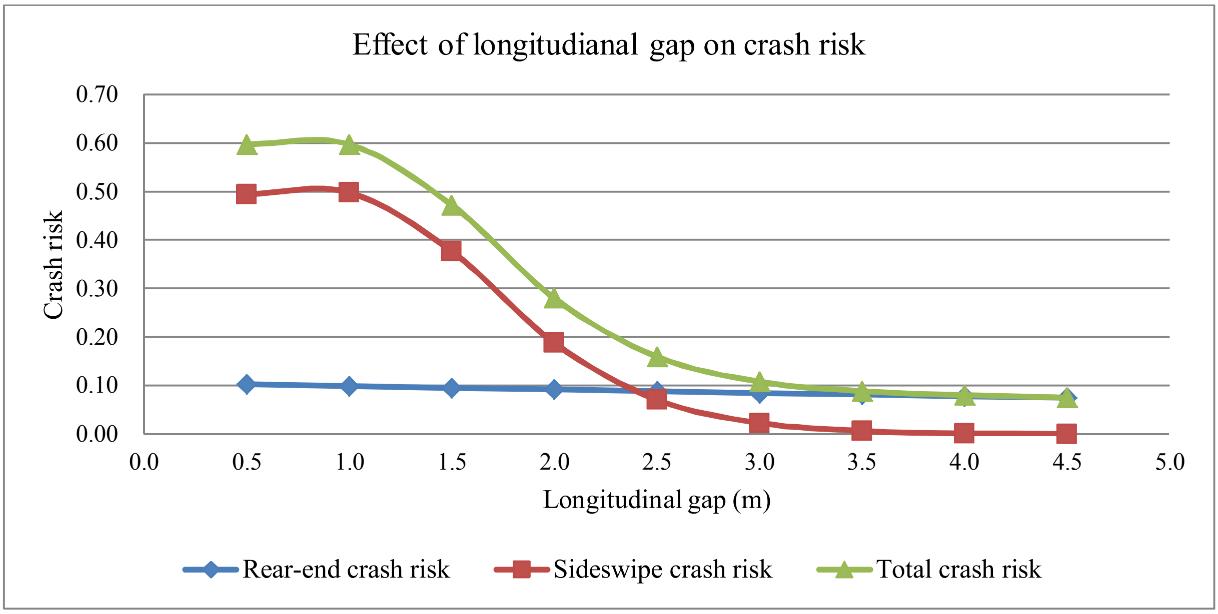


Figure 7.3. The effect of front distance factor on crash risk

7.3.4 The effect of the lateral clearance variable on crash potential

The lateral clearance variable included in the proposed models represents the non-lane based movement characteristic of motorcycles in the motorcycle-dominated environment. Table 7.5 and Figure 7.4 reveal the outputs of crash risk estimated for different values of the lateral clearance factor ranged from 1.0 m to 5.0 m. The results illustrate that the potential of sideswipe crash increases with an increase in the lateral clearance values while the rear-end crash potential decreases correspondingly with an increase of this factor. This may be due to that motorcyclists are more likely to choose the swerving manoeuvre behaviour to overtake the front vehicles as the lateral clearances increase and this results in the higher risk of sideswipe crash. However, the total crash risk shows a decreasing trend on the lateral clearance increase and this may be explained by that the proportion of rear-end crash risk is greater than that of sideswipe crash risk and thus the decrease in rear-end crash potential leading to the decrease in the overall risk.

Table 7.5. The effect of lateral clearance on crash risk

Lateral clearance (m)	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
Rear-end crash risk	0.182	0.165	0.137	0.102	0.066	0.039	0.021	0.011	0.005
Sideswipe crash risk	0.014	0.026	0.045	0.069	0.093	0.111	0.124	0.130	0.134
Total crash risk	0.20	0.19	0.18	0.17	0.16	0.15	0.14	0.14	0.14

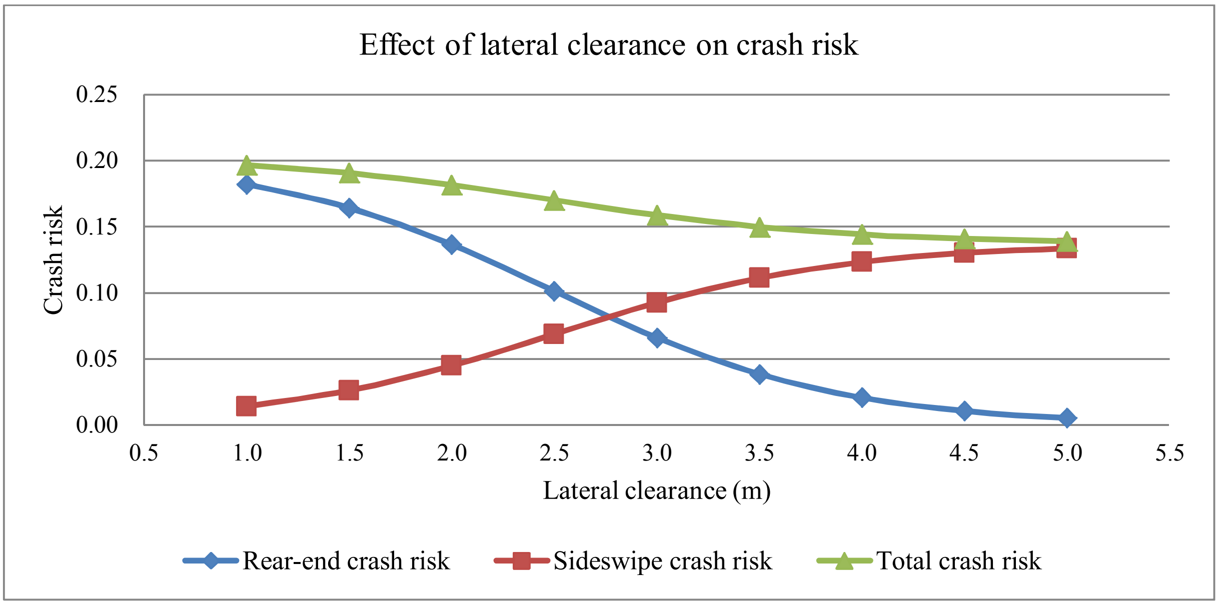


Figure 7.4. The effect of lateral clearance factor on crash risk

7.3.5 The effect of the speed variable on crash potential

The speed variable included in the proposed models affects both the manoeuvre choice behaviour and the threshold safety distance of a motorcycle. Therefore, the speed of motorcycles is an important factor influencing the crash risk output. To investigate the contribution of this factor to the crash risk, the crash potentials are estimated for different levels of the motorcycles' speed as shown in Table 7.6 and Figure 7.5. The results reveal that the crash potentials increase as the speeds of motorcycles increase. The crash risk increases dramatically when the motorcycles' speeds are higher than 30 km/h. This finding may be used as a guidance in designing treatment measures to reduce the crash risk regarding to this contributing factor.

Table 7.6. The effect of speed factor on crash risk

Speed (km/h)	15	20	25	30	35	40	45	50	55	60
Rear-end crash risk	0.01	0.03	0.05	0.07	0.09	0.11	0.12	0.14	0.15	0.16
Sideswipe crash risk	0.00	0.00	0.00	0.00	0.08	0.20	0.30	0.37	0.42	0.45
Total crash risk	0.01	0.03	0.05	0.07	0.17	0.31	0.42	0.51	0.57	0.60

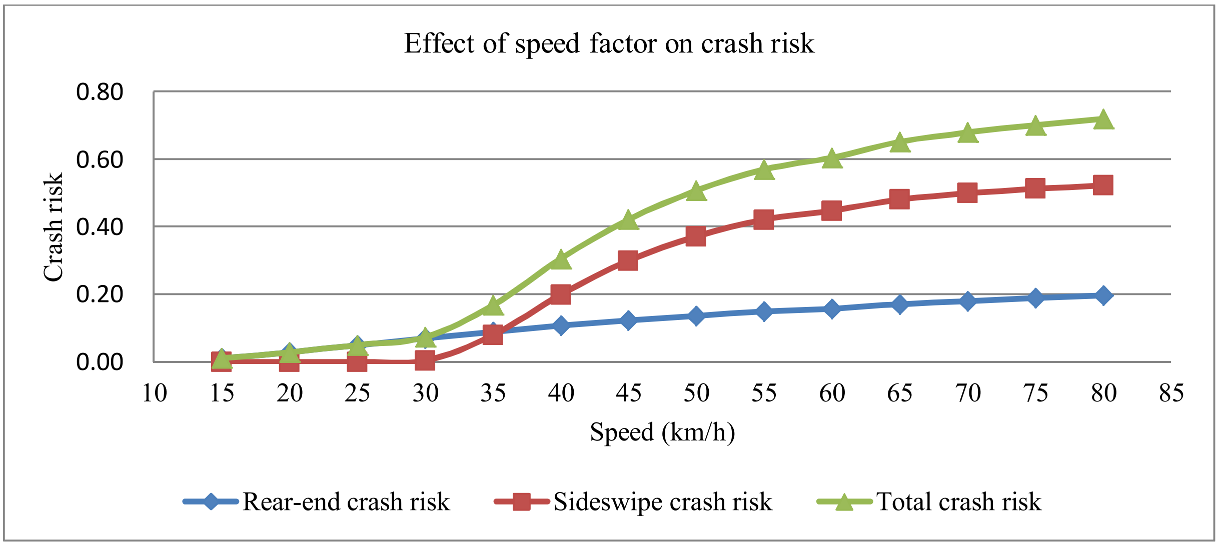


Figure 7.5. The effect of motorcycle speed on crash risk

7.3.6 The effect of the traffic density variable on crash potential

The traffic density is defined in this study as the number of motorcycles moving in the road segment of length 100.0 m and of width 10.0 m. Therefore, the effects of the traffic volume and the road width attributes on crash risk were taken into consideration in the traffic density factor. The traffic density factor represents the current traffic condition in which the motorcyclists take their riding tasks. This factor affects (a) the speed that the motorcyclists choose to move in the traffic stream and (b) the gaps they choose to maintain with their surrounding vehicles, and therefore this variable significantly affects the potential of crashes. To investigate the effect of this factor, the crash risk outputs are estimated at different traffic density conditions. The results are shown in Table 7.7 and Figure 7.6. The outputs illustrate that the rear-end crash potentials increase with increasing values of traffic density and reaches a peak at the value of 150 motorcycles/1000 m^2 and then slightly decreases above this. As may also be seen, the sideswipe crash risk increases as traffic density increases and reaches a peak at 100 motorcycles/1000 m^2 and then decreases slightly to approach to zero when the density is 150 motorcycles/1000 m^2 and higher. This may be due to that motorcycles can manoeuvre freely in the low traffic density (less than 100 motorcycles/1000 m^2), implying that they tend to move at high speeds and change their directions frequently in this traffic condition. Therefore, the potentials of both rear-end and sideswipe crash risk increase significantly. In higher traffic density conditions (from 100 motorcycles/1000 m^2 to 150 motorcycles/1000 m^2), it seems that motorcyclists feel some restrictions to perform swerving manoeuvre behaviour and therefore most of them tend to choose the following manoeuvre. Consequently, the sideswipe crash risk is more likely to reduce while the rear-end crash risk still increases in this situation. In the extremely high traffic density condition (from 150 motorcycles/1000 m^2 onwards), it is observed that the motorcycles cannot perform the swerving manoeuvre freely and are likely to move with a lower speed. Therefore, the potential of sideswipe crashes approach zero and the rear-end crash potential also tends to decrease in this case. For example, this situation can be observed in the congested traffic where motorcyclists normally travel at very low speeds and they cannot perform any swerving manoeuvre behaviour to overtake the front vehicles. The crash risk of this situation is therefore rather low but it is not desirable as vehicles cannot move in the traffic.

Table 7.7. The effect of traffic density on crash risk

Density (motorcycles/1000m2)	**60**	**65**	**70**	**75**	**80**	**85**	**90**	**95**
Rear-end crash risk	0.06	0.07	0.08	0.09	0.10	0.11	0.12	0.14
Sideswipe crash risk	0.05	0.06	0.07	0.08	0.09	0.10	0.10	0.11
Total crash risk	0.11	0.13	0.15	0.17	0.19	0.21	0.23	0.24

Density (motorcycles/1000m2)	100	105	110	115	120	125	130	135
Rear-end crash risk	0.15	0.17	0.18	0.20	0.21	0.23	0.24	0.25
Sideswipe crash risk	0.11	0.10	0.09	0.08	0.06	0.04	0.03	0.01
Total crash risk	0.26	0.27	0.27	0.28	0.27	0.27	0.26	0.26
Density (motorcycles/1000m2)	**140**	**145**	**150**	**155**	**160**	**165**	**170**	**175**
Rear-end crash risk	0.25	0.26	0.26	0.25	0.25	0.23	0.22	0.20
Sideswipe crash risk	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total crash risk	0.26	0.26	0.26	0.25	0.25	0.23	0.22	0.20

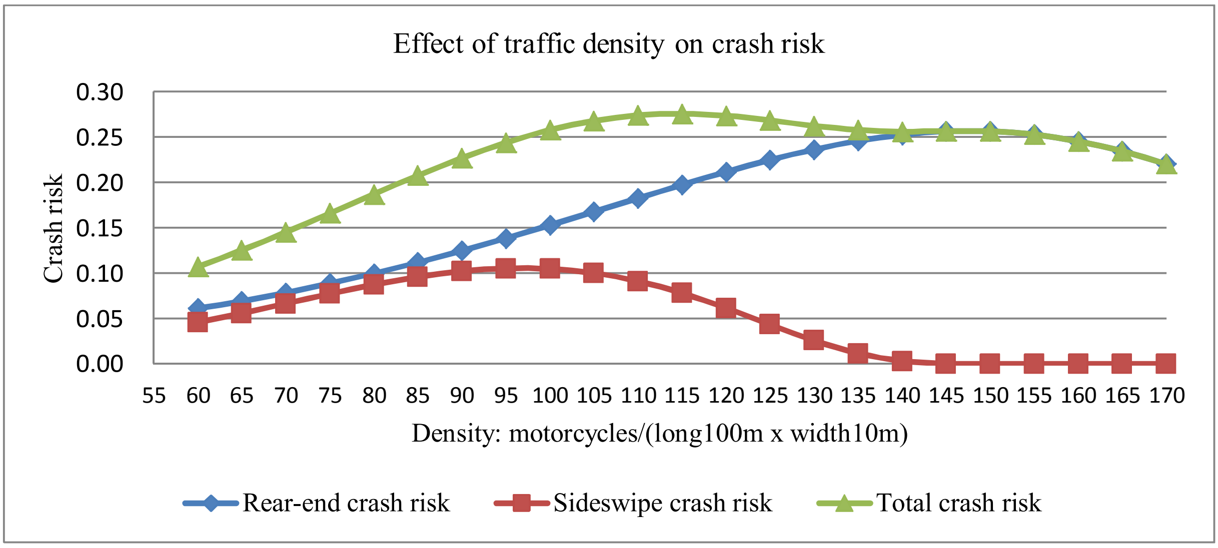


Figure 7.6. The effect of traffic density on crash risk

7.4. Conclusion

In this chapter, the independent variables included in the proposed models were investigated for their effects on the potential of rear-end and sideswipe crashes. These variables including speed, the speed difference, the traffic density, the front distance, the longitudinal gap, the lateral clearance and the road surface condition were found to have a significant contribution to both rear-end and sideswipe crashes risk for motorcycles. These findings may be used as a guidance to develop appropriate countermeasures to reduce the crash potential affected by these contributing factors.

CHAPTER 8

MODEL VALIDATION

This chapter presents the process of validating the developed models. The purpose of the model validation task is to assess the predictive capabilities of the methodology developed in this study. The validation effort for the proposed crash risk models consists of three tasks:

- Assessing the goodness-of-fit
- Field validation
- Validation Test

These three validation tasks are presented in the following three main sections.

8.1. Assessing the Goodness-of-Fit

The purpose of assessing the goodness-of-fit of the model is to test how effective the model is in describing the outcome variable. This task focuses on assessing the fit of the proposed model in capturing the movement characteristics of a motorcycle in a motorcycle-dominated traffic environment that has been found to be a major cause leading to rear-end crash and sideswipe crash potentials.

8.1.1 Methodology

Assessing the goodness-of-fit of the model is the process of comparing the predicted outcomes of the model against the observed values. Suppose that the observed sample values of the outcome variable is denoted by the vector y, where $y' = (y_1, y_2, \dots, y_n)$, and the values predicted by the model is denoted by the vector $\hat{y}$, where $\hat{y}' = (\hat{y}_1, \hat{y}_2, \dots, \hat{y}_n)$. It is concluded that the model fits if (1) summary measures of the difference between $y'$and $\hat{y}'$ are small and (2) the contribution of each pair (y_i, $\hat{y}_i$), i = 1, 2, …, n to these measures is unsystematic and is small relative to the error structure of the model (Hosmer and Lemeshow, 1989). The summary measures of the difference between the observed and fitted values are functions of a residual defined as the difference between the observed and fitted values. This study applied the most often used test method for goodness-of-fit statistic proposed by Hosmer and Lemeshow (1980).

8.1.2 Data description

For this task, the dataset containing 535 observations of the trajectories of 108 subject motorcycles and 2140 observations of 432 influential vehicles from Nguyen Van Linh Street was used.

8.1.3 Results and discussions

To test the goodness-of-fit of the developed model, Hosmer and Lemeshow (1980) proposed a grouping method based on the values of the estimated probabilities. According to this method, 535 observations of motorcycle trajectories was divided into 10 groups that result in the first group containing 54 subjects having the largest estimated probabilities, and the last group containing 49 subjects having the smallest estimated probabilities. For example with group 1, the estimate values are obtained by summing the estimated probabilities over all subjects in this group. As shown in Table 8.2, the total estimated probabilities of group 1 is 53.99. The estimate values of other group were calculated similarly to group 1. The results are shown in the contingency Table 8.1 and they were used to calculate the agreement between the observed and estimated values as shown in Table 8.2. A comparison of the observed and expected frequencies in Table 8.2 shows that the model fits quite well. As illustrated in Table 8.2, the overall agreement percentage of the predicted to the observed values reaches 94.0 per cent, implying that the proposed model predicts the movements of motorcycles in a motorcycle-dominated traffic environment with a high degree of accuracy.

Table 8.1. Contingency Table for Hosmer and Lemeshow Test

Groups	choice = 0 (following manoeuvre)		choice = 1 (swerving manoeuvre)		Total
	Observed	Expected	Observed	Expected	
1	54	53.990	0	0.010	54
2	54	53.801	0	0.199	54
3	54	51.694	0	2.306	54
4	31	36.856	23	17.144	54
5	11	8.474	43	45.526	54
6	2	1.050	52	52.950	54
7	0	0.113	54	53.887	54
8	0	0.019	54	53.981	54
9	0	0.002	54	53.998	54
10	0	0.000	49	49.000	49

Table 8.2. Classification Table

Observed		Predicted		
		choice		Percentage Correct
		0	1	
choice	0	190	16	92.2
	1	16	313	95.1
Overall Percentage				94.0

8.2. Field Validation

The main purpose of the field validation is to test the performance capability of the proposed models in the real-world by comparing the predictive conflict frequency produced by the proposed models with the actual conflict frequency observed in the field.

8.2.1 Methodology

The methodology used for the field validation task is based on comparing the observed conflict frequency with the estimated conflict frequency. This validation task was conducted in two steps. First, rear-end conflict and sideswipe conflict frequencies were observed in the field for different time periods in a day in order to fully capture the frequency of conflict for both peak hours and non-peak hours. Second, the frequencies of rear-end and sideswipe conflicts were predicted using the proposed models for those same time periods and then the estimate results were compared with the actual conflict frequency observed in the field by determining the percentage agreement of the estimated with observed values.

8.2.2 Data description

The dataset from Nguyen Tri Phuong Street was used for this field validation task (Chapter 5). The statistical properties of variables from this dataset were used to estimate the rear-end and sideswipe conflict frequency of each hour for six hours from 6:00 am to 9:00 am and from 3:00 pm to 6:00 pm. These estimate results were then used to compare with the observations of these conflict types for those same period times. The traffic volume and traffic density for each hour used to estimate conflict frequency are described in Table 8.3.

Table 8.3. Traffic volume and density for various time periods

Time periods	Traffic volume (motorcycles/hour)	Average density (motorcycles/1000m^2)	Average speed (m/s)
6:00am-7:00am	3137	74	9.75
7:00am-8:00am	4297	102	8.72
8:00am-9:00am	3471	82	9.45
3:00pm-4:00pm	2971	70	9.91
4:00pm-5:00pm	3975	90	9.15
5:00pm-6:00pm	5284	125	7.95

8.2.3 Results and discussions

The comparison results are shown in Table 8.4. The results reveal that the percentage agreement of the estimated and observed conflict frequency for each time period range from 78.5% to 89.8%. This indicates that the crash risk models developed in this study produce good estimates for both rear-end and sideswipe crash potentials for motorcycles in a motorcycle-dominated traffic environment.

Table 8.4. Conflict frequency outcome and comparison results

Time periods	Predicted conflicts			Observed conflicts (*)			Percentage correct (%)
	Rear-end	Sideswipe	Total	Rear-end	Sideswipe	Total	
6:00am-7:00am	7.4	3.6	11.0	9	5	14	**78.5**
7:00am-8:00am	32.7	8.1	40.8	27	10	37	**89.8**
8:00am-9:00am	19.6	11.8	31.4	24	14	38	**82.6**
3:00pm-4:00pm	4.1	1.7	5.8	5	2	7	**83.0**
4:00pm-5:00pm	18.6	8.8	27.3	22	12	34	**80.4**
5:00pm-6:00pm	57.3	12.9	70.2	46	15	61	**84.9**

(*): *Conflicts were observed directly in the field via video recordings*

8.3. Validation Test

The main purpose of this validation test is to assess the predictive capabilities of the methodology developed in this study. The first purpose of this test is to afford a correlation of the crash potentials produced by the proposed models with actual crash history. The second purpose of this test is to identify any correlation between the output of the proposed models and the existing methodologies available from the literature. Two existing methodologies employed for this validation task are: (1) the crash prediction methodology developed by the Highway Safety Manual (HSM) (AASHTO, 2009) and (2) the crash risk assessment methodology developed by the International Road Assessment Programme (iRAP, 2013). Further details of these methodologies are found in Chapter 2.

8.3.1 Methodology

The methodology used for the validation test is based on the correlation of the actual historical crash data from real-world roads with the corresponding outputs of the same roads from the crash risk models developed in this study. In this test, the ranking of locations from the proposed models according to the average daily conflict frequency was compared to the ranking of those same locations from the actual annual crash frequency, the existing iRAP methodology and the existing HSM methodology. The output of the proposed models is the average daily conflict frequency while that of the iRAP methodology is the Star Rating Score and that of the HSM methodology is the average annual crash frequency. Therefore, the ranking comparison technique was applied to compare the predictive capability of these methodologies. This validation test process was conducted in the following five steps (A, B, C, D and E):

Step A: Proposed model ranking

In this step, the average daily frequencies of rear-end and sideswipe conflicts were estimated for each location using the crash risk models developed in this study. These locations were then ranked based on the total number of conflicts in ascending order.

Step B: HSM model ranking

In this step, the average yearly crash frequencies for a road segment were determined using the predictive methodology presented in the Highway Safety Manual (HSM) (ASSHTO, 2009). The annual frequencies of rear-end and sideswipe crash were estimated for each location using the safety performance functions (SPF). These locations were then ranked based on the predicted average annual crash frequencies in ascending order.

Step C: iRAP model ranking

In this step, Star Rating Scores (SRS) and average yearly fatalities for each road segment were estimated using the methodology developed by the International Road Assessment Programme (iRAP methodology, 2013). In the existing iRAP methodology, rear-end and sideswipe crash types are not included in Star Rating Score system. Therefore, for the purpose of this test, it was assumed that both rear-end and sideswipe crash were taken into account in the iRAP SRS system by the along crash type. However, the SRS value of along crash type for all selected road segments were not different, therefore these locations were ranked based on an estimate of average annual fatalities in ascending order.

Step D: Actual crash ranking

In this step, the average yearly actual crash frequencies for each road segment were determined by dividing the total number of historical crashes collected over the period from 2008 to 2015 by the number of years of this period. These locations are then ranked based on their average annual actual crash history in ascending order.

Step E: Ranking comparison

In this step, the road segment rankings based on the crash risk models developed in this study, the HSM model and the iRAP model were compared to the road segment rankings based on average yearly actual crash frequencies. To determine the level of agreement between these rankings, the Spearman rank correlation coefficient was used in this test. This is a nonparametric statistical test and thus it is appropriate to use for this purpose. According to this method, there is a perfect correlation between two rankings if the value of correlation coefficient is 1.0 and there is no correlation between them if the value of coefficient is 0.0. The Spearman rank correlation coefficient (ρ_s) is calculated as follows:

$$\rho_s = 1 - \frac{6\sum d_i^2}{n(n^2 - 1)}$$

where,

d_i: is the difference between two rankings for sample i

n: is the number of samples ranked

8.3.2 Data description

Ten road segments on ten different roads in the city of Danang in Vietnam were selected for this validation test. The geometry and traffic characteristics of these road segments are described in Table 8.5 and Table 8.6. The average annual actual crash history occurring on these roads was used to examine the relation with the proposed model, the iRAP model and the HSM model. To identify the average yearly crash frequency, this study collected the historical crash data (per 1000m of road length) for the period of eight years from 2008 to 2015 and calculated the average crash per year by dividing the total number of crashes by the number of eight years. The total numbers of crashes over 8 years for different roads were collected from Danang Department of Transport as reported in Table 8.6.

Table 8.5. Geometry characteristics of road segments

Location	Road name	Road length (m)	Number of lanes	Lane width (m)
1	Nguyen Van Linh	2170	2	4
2	Bach Dang	2542	4	3.75
3	Duong 2-9	3377	3	3.5
4	Nguyen Tri Phuong	1295	2	3.5
5	Dien Bien Phu	2700	4	3.5
6	Nguyen Huu Tho	4680	3	3.5
7	Cach Mang T-8	1000	3	3.5
8	Nguyen Tat Thanh	2000	3	3.5
9	Truong Chinh	1000	3	3.5
10	Ton Duc Thang	1000	3	3.5

Table 8.6. Traffic characteristics of road segments and historical crash data

Location	Volume (vehicles/day)	Density (vehicles/1000m^2)	Average speed (m/s)	Crash records (2008-2015) (serious and fatal motorcycle - motorcycle crashes)	
				Rear-end	Sideswipe
1	59704	89	9.68	21	5
2	41621	68	9.99	9	2
3	49706	72	9.83	16	4
4	61402	94	9.48	27	7
5	78945	76	9.19	35	9
6	32706	72	9.83	11	3
7	43857	75	9.71	12	4
8	28865	68	9.99	11	2
9	65551	83	9.41	27	15
10	67563	85	9.33	24	14

- Historical crash data collection source: Danang Department of Transport

8.3.3 Results and discussions

Table 8.7 shows the average daily conflict frequency estimated by the proposed models (RE, SW: the number of rear-end and sideswipe conflicts respectively; TT: total of rear-end and sideswipe conflicts), the average annual crash frequency estimated by the HSM methodology (RE, SW: the frequencies of estimated average annual rear-end and sideswipe crashes respectively; TT: total of average annual rear-end and sideswipe crashes), the star rating score and average annual fatalities estimated by the iRAP methodology (SRAS-A, SRS-T: star rating scores of along crash type and all crash types respectively; Fa-TT: estimated average annual fatalities of all crash types) and the average annual actual crash data (RE, SW: observed average annual rear-end and sideswipe crashes) for 10 selected road segments and their rankings. Table 8.8 shows the Spearman rank correlation coefficient values of six comparisons. Compared with the HSM methodology and iRAP methodology, the methodology developed in this study presents the strongest correlation with the actual crash history. The correlation coefficient value for the proposed methodology is 0.98 while those of for the HSM methodology and iRAP methodology are 0.91 and 0.87 respectively. This implies that the proposed models produce a reliable estimate of crash potentials which were found to have a strong association with the actual crash frequency data for the data set considered.

Table 8.7. Outputs and rankings for locations

Locations	**Average daily conflict estimated by the proposed models**				**Average annual actual crash history**			
	RE	SW	TT	Ranking	RE	SW	TT	Ranking
1	190	41	231	**6**	2.7	0.6	3.3	**6**
2	42	11	52	**2**	1.1	0.3	1.4	**1**
3	121	31	152	**5**	2.0	0.5	2.5	**5**
4	308	74	381	**7**	3.4	0.8	4.2	**7**
5	511	128	639	**10**	4.4	1.1	5.5	**10**
6	42	13	55	**3**	1.4	0.4	1.8	**3**
7	82	31	113	**4**	1.5	0.5	2.0	**4**
8	22	5	27	**1**	1.3	0.3	1.6	**2**
9	280	153	433	**8**	3.4	1.8	5.2	**9**
10	346	200	546	**9**	3.0	1.8	4.8	**8**
Locations	**Average annual crash frequency estimated by HSM methodology**				**SRS and average annual fatalities estimated by iRAP methodology**			
	RE	SW	TT	Ranking	SRS-A	SRS-T	Fa-TT	Ranking
1	0.5	0.1	0.6	**4**	0.2	0.8	0.02	**2**
2	0.3	0.1	0.4	**2**	0.2	0.8	0.01	**1**
3	0.4	0.1	0.5	**3**	0.2	0.8	0.01	**1**
4	0.5	0.1	0.6	**4**	0.2	0.8	0.02	**2**
5	0.6	0.1	0.8	**6**	0.2	0.8	0.02	**2**
6	0.3	0.1	0.3	**1**	0.2	0.8	0.01	**1**
7	0.3	0.1	0.4	**2**	0.2	0.8	0.01	**1**
8	0.2	0.1	0.3	**1**	0.2	0.8	0.01	**1**
9	0.5	0.1	0.6	**4**	0.2	0.8	0.02	**2**
10	0.5	0.1	0.7	**5**	0.2	0.8	0.02	**2**

RE: rear-end; SW: sideswipe; TT: total of rear-end and sideswipe; SRS-A: star rating score for along crash types; SRS-TT, Fa-TT: star rating score and average annual fatality for total crash type respectively.

Table 8.8. Correlation coefficient

Methodology	HSM methodology	iRAP methodology	Actual crash
Proposed methodology	0.96**	0.87**	0.98**
HSM methodology		0.89**	0.91**
iRAP methodology			0.87**

** Correlation is significant at the 0.01 level

8.4. Summary

The validation results presented in this chapter indicated that the developed methodology produced a good estimate of both rear-end and sideswipe crash risk for motorcycles in a motorcycle-dominated traffic environment for the data set considered. In addition, the validation test showed that the proposed methodology presented the strongest correlation with the actual historical crashes and produced consistent and slightly better estimates compared with the HSM methodology and iRAP methodology for motorcycles in this particular traffic environment.

CHAPTER 9

MODEL APPLICATION: RELATIVE RISK ASSESSMENT

This chapter presents the application of the developed models in selecting countermeasures to reduce the crash risk for motorcycles in motorcycle-dominated traffic environments of urban areas. The chapter is organised in two main sections. The first section proposes a new concept of the Conflict Modification Factor (CoMF) used to assess the relative contribution of risk factors on the potential of both rear-end and sideswipe crashes. The second section identifies several potential countermeasures related to risk factors included in the developed models that may be considered to implement for the improvement of motorcyclists safety.

9.1. Assessing the Relative Contribution of Risk Factors

By evaluating the relative contribution of risk factors to the sequence of traffic events, crashes and crash severities may be reduced by implementing specific countermeasures to target specific risk factors. In addition, the relative contribution of risk factors to crashes may assist in determining how to best allocate available resource to a safety improvement programme (ASSHTO' HSM, 2009). This section presents the application of the existing Crash Modification Factor (CMF) in measuring the relative contribution of risk factors and then proposes a new concept of the CoMF as a surrogate measure to CMF. They are as follows.

9.1.1 Crash Modification Factor (CMF)

CMFs represent the relative change in the crash frequency due to the change in one specific condition (e.g. widening road width) while all other conditions remain constant. Therefore, a CMF may be used to evaluate the effect of a particular road infrastructure attribute or traffic condition on the likelihood of crashes and severities or the change in crashes due to the implementation of a particular countermeasure (HSM, 2009; Gross et al., 2010; Carter et al, 2012). CMFs are defined as the ratio of the expected average crash frequency of a specific location under one condition to the expected average crash frequency of the same location under a different condition. The different condition is often the base condition (HSM, 2009). A CMF may be calculated as follows:

$$CMF = \frac{crash\ frequency\ with\ condition\ 1}{crash\ frequency\ with\ condition\ 2}$$

(Equation 9.1)

CMFs defined in Equation (9.1) may be used to compare the predicted crash frequency between “condition 1” and “condition 2” for a specific location. The values of CMFs are determined in relation to the base condition that is presented as “condition 2” in Equation (9.1). Under the base condition (e.g. with no change in the conditions), the value of a CMF is 1.0. CMF values less than 1.0 indicate that the countermeasure reduces the estimated average crash frequency in comparison to the base condition. CMF values greater than 1.0 indicate the countermeasure increases the estimated average crash frequency in comparison to the base condition. CMF is usually used as a tool to evaluate the effectiveness of a countermeasure (HSM, 2009).

CMFs have been applied in several existing road safety assessment system such as the Highway Safety Manual (ASSHTO, 2009) and the International Road Assessment Programme (iRAP, 2013). In the iRAP Star Rating methodology, CMFs are applied to calculate the scores of crash types for different road users based on an assessment of road attributes related to the likelihood and severity of crashes for a specific road segment (section 2.2.2). In the Highway Safety Manual, CMFs are used for the following purposes (section 2.2.1):

- A CMF is multiplied with a crash frequency of base conditions determined by a Safety Performance Function (SPF) to estimate the average crash frequency for a specific site under the existing conditions based on an assessment of existing geometric design and traffic control features. The CMFs are used to assess the difference of crash frequency between the base conditions and the existing conditions.
- A CMF is multiplied with the observed crash frequency of a specific site that is being considered for implementing countermeasures to estimate the change in the expected crash frequency after a countermeasure is implemented. The CMFs are used to assess the difference of crash frequency before and after implementing a countermeasure.

9.1.2 The concept of the Conflict Modification Factor (CoMF)

In low-income and middle-income countries, obtaining reliable crash data to determine CMFs is a difficult task due to the under-reporting of accidents and the poor quality of historical crash data. Therefore, this study proposes a concept of the Conflict Modification Factor (CoMF) that may be used as a surrogate measure to CMF in road safety analysis due to the following reasons:

- There is statistical relationship between the frequency of conflict and crash events (Amundsen and Hydén, 1977; Miglez, Glauz and Bauer, 1985; Hydén, 1987; Svensson, 1992; Archer, 2004; Gettman *et al.,* 2008; HSM, 2009; Ismail, 2010; Laureshyn, 2010; Guo *et al.,* 2010). Gettman *et al.* (2008) found that the ratio of traffic conflicts to actual crashes may be 20,000 to 1.
- The causal mechanisms for both conflict and crash events are similar (Guo *et al.,* 2010). According to Laureshyn (2010), the occurrence of a crash is always proceeded by a conflict.
- The effects of contributing factors on the occurrence of conflicts and crashes do not seem to be different (Guo *et al.,* 2010).

The CoMFs proposed in this study represent the relative change in the conflict frequency due to the change in one specific condition while all other conditions remain constant. The process to determine CoMFs is as follow.

Using the theory of probabilities, the likelihood of event occurrence is defined as the ratio of the probability of event occurrence to the probability of event non-occurrence (Guo et al., 2010). Therefore, the likelihood of conflict occurrence may be defined as follows:

$$likelihood\ of\ conflict = \frac{probability\ of\ event\ occurrence}{probability\ of\ event\ nonoccurrence}$$

(Equation 9.2)

Furthermore, based on the approach of determining CMFs as described in previous section, CoMFs may be defined as the ratio of the likelihood of conflicts for a specific location under one condition to the likelihood of conflicts for the same location under a base condition.

Consequently, the ratio of the likelihood of a particular traffic condition to the likelihood of the baseline traffic condition may be used to evaluate the change of conflict frequency between these two conditions. This likelihood ratio is defined as the Conflict Modification Factor (CoMF) and may be expressed by:

$$Conflict\ Modification\ Factor = \frac{likelihood\ of\ conflict_{\ specific\ traffic\ conditions}}{likelihood\ of\ conflict_{baseline\ traffic\ conditions}}$$

(Equation 9.3)

9.1.3 Determining the relative risk value of risk factors

With regard to Equation (9.3), a risk factor contributes significantly to conflict occurrence if the likelihood of conflict for a particular traffic condition is much higher than the likelihood of conflict for the baseline traffic condition. The baseline traffic condition is defined in this study as the normal driving condition in which motorcyclists can move freely in a traffic stream at a low crash risk level. Using the proposed crash risk models, CoMFs may be developed for each of their variables (e.g. operating speed, speed difference, traffic density, front distance, longitudinal gap, lateral clearance, lateral gap, road surface condition, segregated motorcycle lane) based on the sensitivity analysis outputs as presented in Chapter 7. The potential of a crash is defined as a conflict (or near-crash) event potentially resulting in a crash and therefore the CoMF of a risk factor may be defined as the relative risk value representing the changes in crash potentials due to the change of that particular risk factor. The relative risk values (CoMFs) of these variables are presented in Table 9.1 through to Table 9.9. An example of calculating the relative risk value for a contributing factor using Equations (9.2) and (9.3) is presented in Appendix A.

a) The relative risk value of the operating speed factor

Table 9.1 shows the relative risk values of the operating speed factor for rear-end crash and sideswipe crashes. This factor has been found to have a significant contribution to both rear-end crash and sideswipe crashes. The risk values indicate the higher the speed of vehicle the higher the rear-end crash and side swipe crash risk.

Table 9.1. Relative risk values of operating speed factor

Speed (km/h)	25	30	35	40	45	50	55	60	65	70
Rear-end crash	0.5	0.8	1.0	1.2	1.4	1.6	1.8	1.9	2.1	2.3
Sideswipe crash	0.0	0.1	1.0	2.9	5.0	7.0	8.6	9.6	10.9	11.8

b) The relative risk value of the speed difference factor

Table 9.2 shows the relative risk values for various speed differences for rear-end crash and sideswipe crash type. This factor has been found to have a significant contribution to sideswipe crashes and the higher the difference in speed between the motorcycles and the front vehicles the higher the sideswipe crash risk. The rear-end crash risk decreases if the speed differences are higher than 2.5 km/h while the sideswipe crash risk increases significantly from this value.

Table 9.2. Relative risk values of the speed difference factor

Speed difference (km/h)	-7.5	-5.0	-2.5	0.0	2.5	5.0	7.5	10.0	12.5	15.0
Rear-end crash	0.0	0.1	0.5	1.0	1.2	1.0	0.5	0.3	0.2	0.1
Sideswipe crash	0.1	0.1	0.4	1.0	2.2	4.1	5.9	7.0	7.3	7.4

c) The relative risk value of the traffic density factor

Table 9.3 shows the relative risk values of traffic density factor for rear-end crash and sideswipe crash type. In order to simplify the presentation, it was assumed that the traffic density conditions may be categorised by six levels in which each level was determined by grouping all traffic density values found to have similar influence on crash risk. Consequently, six levels of traffic density conditions were determined as follows:

(1) "Free flow" condition denoted for the traffic density has a value of under 70 motorcycles/1000 m^2,

(2) "Very low restricted flow" condition denoted for the traffic density has a value of from 70 to under 90 motorcycles/1000 m^2,

(3) "Low restricted flow" condition denoted for the traffic density has a value of from 90 to under 115 motorcycles/1000 m^2,

(4) "Moderate restricted flow" condition denoted for the traffic density has a value of from 115 to under 140 motorcycles/1000 m^2,

(5) "High restricted flow" condition denoted for the traffic density has a value of from 140 to under 165 motorcycles/1000 m^2,

(6) "Very high restricted flow" condition denoted for the traffic density has a value of greater than 165 motorcycles/1000 m^2.

The relative risk values for various traffic density conditions are shown in Table 9.3. Under very high traffic (e.g. nearly congestion), both rear-end crash and sideswipe crash present a low risk. The sideswipe crash type approaches the highest risk in low traffic density conditions where most motorcycles choose to perform swerving manoeuvres. As also it may be seen from the risk values that the higher the traffic density condition the higher the rear-end crash risk.

Table 9.3. Relative risk values of traffic density condition

Traffic density	Free flow (< 70 motorcycles /1000 m^2)	Very restricted flow (70 - 90 motorcycles /1000 m^2)	Low restricted flow (90 - 115 motorcycles /1000 m^2)	Moderate restricted flow (115 - 140 motorcycles/1000 m^2)	High restricted flow (140 - 165 motorcycles /1000 m^2)	Very high restricted flow (> 165 motorcycles /1000 m^2)
Rear-end crash	0.75	1.0	2.0	3.0	3.5	2.5
Sideswipe crash	0.75	1.25	1.5	0.5	0.25	0.10

d) The relative risk value of the front distance factor

Table 9.4 shows the relative risk values for front distances for rear-end crash and sideswipe crash type. Front distance has a significant contribution to sideswipe crashes and the shorter the front distance the higher the sideswipe crash risk. The rear-end crash risk slightly increases with the increase of front distance and slightly decreases when front distances are 3.0 m or higher.

Table 9.4. Relative risk value of the front distance factor

Front distance (m)	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
Rear-end crash	0.5	0.8	1.0	1.1	1.0	0.8	0.5	0.4
Sideswipe crash	3.0	2.7	2.3	1.6	1.0	0.5	0.2	0.1

e) The relative risk value of the longitudinal gap factor

Table 9.5 shows the relative risk values for various longitudinal gaps for rear-end and sideswipe crashes. This factor has been found to have a significant contribution to the sideswipe crashes and it affects insignificantly rear-end crash risk. The risk values indicate the shorter the longitudinal gap between the laterally-following vehicle and the motorcycle the higher the sideswipe crash risk.

Table 9.5. Relative risk values of longitudinal gap factor

Longitudinal gap (m)	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5
Rear-end crash	1.1	1.1	1.0	1.0	1.0	0.9	0.9	0.8
Sideswipe crash	12.9	7.9	3.0	1.0	0.3	0.1	0.05	0.01

f) The relative risk value of the lateral clearance factor

Table 9.6 shows the relative risk values for varying lateral clearances for rear-end and sideswipe crashes. This factor has been found to have a significant contribution to rear-end crashes while its influence on sideswipe crashes is less. The risk values indicate the higher the lateral clearance of the front vehicle the lower the rear-end crash risk while the higher the lateral clearance the higher the sideswipe crash risk.

Table 9.6. Relative risk values of lateral clearance factor

Lateral clearance (m)	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
Rear-end crash	3.1	2.8	2.2	1.6	1.0	0.6	0.3	0.2	0.1
Sideswipe crash	0.1	0.3	0.5	0.7	1.0	1.2	1.4	1.5	1.5

g) The relative risk value of the lateral gap factor

Table 9.7 shows the relative risk values of the lateral gap factor for rear-end and sideswipe crash risk. This factor has been found to have a significant impact on sideswipe crash risk when the lateral gap less than 1.5 m while the factor does not affect rear-end crash risk.

Table 9.7. Relative risk values of lateral gap factor

Lateral gap (m)	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5
Rear-end crash	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Sideswipe crash	3.8	2.4	1.0	0.1	0.05	0.05	0.05	0.05	0.05

h) The relative risk value of the road surface condition factor

Table 9.8 shows the relative risk values for two road surface conditions for rear-end and sideswipe crashes. It has been found that both rear-end and sideswipe crash risk increase when the road surface is wet.

Table 9.8. Relative risk values for road surface condition factor

Road surface condition	Dry Pavement	Wet Pavement
Rear-end crash	1.00	1.1
Sideswipe crash	1.00	1.7

i) The relative risk value of the segregated motorcycle lane presence factor

Table 9.9 shows the relative risk values for segregated motorcycle lanes for rear-end and sideswipe crashes. It has been found that the presence of segregated motorcycle lanes will lead to a decrease in both rear-end and sideswipe crash risk.

Table 9.9. Relative risk values of segregated motorcycle lane presence

Segregated motorcycle lane	Non-presence	Presence
Rear-end crash	1.00	0.66
Sideswipe crash	1.00	0.43

9.2. Several Countermeasures for Improving Motorcyclist Safety

Countermeasures are developed to reduce the frequency of crashes and their severity. Therefore, to determine appropriate measures to reduce the potential of rear-end and sideswipe crashes for motorcyclists, it is critical to investigate the contribution of risk factors to the occurrence of these two crash types. Using the proposed crash risk models, countermeasures may be developed based on an assessment of the effect of risk factors on the potential of rear-end and sideswipe crashes. These risk factors are: speed of motorcycles, speed difference, traffic density, road surface condition, front distances, longitudinal gaps, lateral gaps and lateral clearances (section 9.1). Consequently, the following possible countermeasures may be proposed:

- Changeable Speed Limit Signs;
- Changeable Gap Warning Signs;
- Changeable Road Surface Condition Warning Signs;
- Segregated Motorcycle Lanes.

The potential effectiveness of these measures in reducing motorcycle crashes in urban traffic environments particularly in Danang, where motorcycles account for over 90% of urban transport and land uses for road infrastructure improvements are limited and expensive, require further verification through, for example, long-term pilot studies. Such studies were beyond the scope and the duration of this research. Yet they are particularly necessary for motorcycle-dominated traffic environments that are frequently found in Southeast Asia countries but not in the rest of the world. However, it should be also noted that the effectiveness of these measures depends on a number of other factors such as the degree to which road users understand and obey traffic laws, the degree of rigorous enforcement applied by the authorities, the reliability and maintenance of the entire traffic system.

Their choice, from a number of other options, may be justified as follows.

9.2.1 Installing "changeable speed limit signs"

Variable mandatory speed limit signs are installed to provide the notice of speed limit for road users in real time. For the proposed models, the speed factor has been found to have a significant contribution to crash potentials. The risk of rear-end and sideswipe crashes increases dramatically when the speed increases, and therefore controlling the speed limit for different road users based on an assessment of traffic conditions in real time may be a potential measure to reduce the crash risk. For example, the speed limit may change with the change of traffic condition in peak hours and nonpeak hours or in various zones of urban areas using active traffic management technology.

The impact of changing a speed limit has been examined in a number of studies in developed countries and the results of these studies have been summarised by Elvik, Christensen and Amundsen (2004). The impact of changing speed limits on crashes, injuries and fatalities will depend on how much vehicles change their speeds in response to a speed limit change (see section 2.7.5). According to Elvik, Christensen and Amundsen (2004), when the speed limit is changed by 10 km/h, the operating speed changes by about 2.5 km/h. In the case of a city such as Danang, the effects of operating speed changes on injuries and fatalities may be estimated according to the model developed in this research. For example, as shown in Table 9.1, when the operating speed decreases from 50 km/h to 45 km/h, the theoretical crash risk of rear-end and sideswipe crashes for motorcycles could be reduced to 0.88 and 0.71 respectively. According to HSM (2009), the provision of advisory speed signs reduces the total number of injury crashes to 0. 87 compared to the absence of signage.

9.2.2 Installing "changeable gap warning signs"

Changeable gap warning signs are installed to provide the notice of threshold safety distances for road users in real time. This warns the drivers to pay attention in maintaining appropriate distances with their neighbouring vehicles to reduce the potential of crashes from occurring. In the proposed models (Equations 6.13 and 6.14), the threshold-safety-distance is used to estimate the potential of crashes and this indicator is affected by both traffic density and road surface condition. Therefore, warning the drivers of unsafe threshold-safety-distances may be an effective measure to prevent the risk of crashes in urban areas where there is high traffic density and availability of appropriate technology. According to Elvik *et al.* (2009), the installation of "close following gap warning signs" reduces the total number of rear-end crashes to 6% compared to the absence of signage. Similarly, using the models developed in this study, the effect of front distances on crash risk may be estimated and it was found that the risks of rear-end and sideswipe crashes reduce up to 25% when the gaps increase 0.5 m (see Table 9.4).

9.2.3 Installing "changeable road surface condition warning signs"

The road surface condition warning signs may be installed to provide notice of the road surface condition to drivers in real time. This warns the drivers to pay more attention and adjust their driving due to adverse conditions such as slippery or wet pavements. As these conditions may reduce the efficiency of braking systems and the potential of crash occurrence may therefore increase. Using the conclusion drawn from the examination of the proposed models it may be induced that installing such signs may be another measure to reduce the crash risk from occurring. As shown in Table 9.8, for example, the risks of rear-end and sideswipe crashes in wet pavement are 0.1 and 0.7 higher than that of in dry pavement respectively.

9.2.4 Providing "segregated motorcycle lanes"

If the proposed models were considered, the probability of motorcycle crashes with heavier vehicles (e.g. passenger car) appears to be higher than that between two motorcycles due to the larger reaction time of drivers and the larger braking distance of vehicles. In addition, this measure also reduces the swerving/weaving manoeuvre and erratic movements of motorcycles that have been found to have a significant contribution to crash risk. This may suggest that the provision of a segregated motorcycle lane is a solution that may reduce crash risk by separating motorcycles and other vehicle types in mixed traffic conditions. It may be provided by installing road markings or rumble strips on the roadway to separately delineate lanes for motorcycles and lanes for passenger cars (iRAP, 2013). It aims to prevent the interactions between motorcycles and other vehicle types and therefore may reduce the likelihood and severity of crashes. A crash that occurs between motorcycles and heavier vehicles can be higher severity (iRAP, 2013). As shown in Table 9.9, the provision of "segregated motorcycle lane" could reduce the risks of rear-end and sideswipe crashes to 0.66

and 0.43 respectively compared to the absence of this treatment. However, this finding together with those shown in Sections 9.2.1 through to 9.2.3 should be further tested and contrasted against those concerning rear-end and sideswipe crashes between motorcycles.

9.3. Conclusion

In this chapter, a new concept of Conflict Modification Factor was proposed to determine the relative risk value of risk factor contributing to the potential of rear-end and sideswipe crashes for motorcycles. Based on assessing the relative contribution of risk factors to the crash potential for motorcyclists, several countermeasures were recommend that may be considered for the motorcyclists safety improvement programme.

CHAPTER 10

APPLICATION: ENHANCING THE iRAP SRS

10.1. Introduction

This chapter suggests an application of the developed crash risk models with the view to enhance the International Road Assessment Programme star rating system (iRAP SRS) for motorcyclists in motorcycle-dominated traffic environments of urban roads. The chapter is organised in four main sections. The first section gives the motivation of choosing the existing iRAP SRS as an area of application of the developed models. The second section discusses the limitation of the existing iRAP SRS for motorcyclists and then its methodology is presented in section three. The final section proposes a methodology to enhance the existing iRAP SRS for motorcyclist by integrating the risk scores of rear-end and sideswipe crash types into the iRAP risk modelling process.

10.2. Motivation of Enhancing the Existing iRAP SRS for Motorcyclists

This study developed models to estimate the potentials of rear-end and sideswipe crash types which has been found to account for a large proportion of multiple vehicle crashes in urban areas (see section 1.2). However, in the real word, particularly in the complex environments of urban areas in low-income and middle-income countries where a greater variety of risk factors contributing to crash risk can be present at the same time and this may lead to the occurrence of various crash types. Therefore, in addition to these two crash types, to overall assess the risk of crashes for an urban road segment, the risk of rear-end and sideswipe crashes estimated in this study may be integrated into the existing International Road Assessment Programme (iRAP) star rating system which assess the risk of other crash types including run-off crash, head-on crash, intersection crash, property access crash, and along crashes.

The purpose of enhancing the existing iRAP Star Rating methodology by integrating the risk of rear-end and sideswipe crash types is to achieve a comprehensive tool for assessing motorcyclist safety in the environment of low-income and middle-income countries where motorcycles are the predominant vehicle types particularly in urban areas. The existing iRAP star rating system was chosen as an area of application of the models developed in this study due to the following reasons:

- The iRAP star rating methodology has been developed to assess the risk for all road user types including motorcyclists in low-income and middle-income countries where motorcycle is the predominant mode of transport.
- The iRAP star rating methodology has focused on assessing a wide range of crash types for motorcyclists but it still does not take into account the rear-end and sideswipe crash types which have been found to account for a large proportion of total motorcycles' crashes in urban areas (Manan and Varhelyi, 2012; DoT, 2013; Ming *et al.,* 2013).
- iRAP is a well-known road safety assessment system that has been used to assess and improve the safety of roads in a wide range of low-income and middle-income countries and the system's strengths have been acknowledged by traffic engineers around the world (Lynam, 2012; iRAP, 2013; Jurewicz *et al.,* 2014).

10.3. Limited Coverage of Crash Types for Existing iRAP Motorcyclist SRS

The motorcyclist star rating score is determined based on assessing the risk of five crash types. However, due to the range of paths that motorcycles can take within traffic streams, those five crash types determined by the existing iRAP star rating score system are likely to capture less of the total motorcycles' crashes (Lynam, 2012). Sideswipe crashes and rear-end crashes away from intersections are found to account for a large proportion of total motorcycles' crashes in urban transport system, particularly in the motorcycle-dominated traffic environment, but these two crash types are not included in the existing motorcyclist star rating score (iRAP, 2013; DoT, 2013; Manan and Várhelyi, 2012; Ming, Wucheng and Cheng, 2013). Therefore, there is a need to enhance the existing motorcyclists SRS by integrating the risk of rear-end and sideswipe crash type into the system.

10.4. The Existing iRAP Star Rating System for Motorcyclists

As stated in section 2.2.2, the existing iRAP star rating system includes four road user types: vehicle occupants, motorcyclists, bicyclists and pedestrians. For each a score is calculated combining scores of various crash types. For motorcyclists, a Star Rating Score (SRS) is produced by calculating the scores for five crash types: Run-off, Head-on, Intersection, Property access, and Along. A motorcyclist SRS is calculated for each 100 metre segment of road using the following equation (iRAP methodology, 2013):

$$\text{Motorcyclist SRS} = (\text{Run-off} + \text{Head-on} + \text{Intersection} + \text{Property} + \text{Along})\ \text{Crash Scores} \qquad \text{(Equation 6.3)}$$

The score of a crash type is expressed by (see section 2.2.2):

$$\text{Crash Score} = \text{Likelihood} \times \text{Severity} \times \text{Operating speed} \times \text{External flow influence} \times \text{Median traversability} \quad \text{(Equation 6.4)}$$

The road attribute risk factors related to the likelihood and severity used to calculate the score of each crash type shown in Table 10.1. The score of a crash type is determined by multiplying the relative risk values of risk factors related to the likelihood and severity. The relative risk values of attribute risk factors used in the iRAP Star Rating methodology are also known as Crash Modification Factors (CMFs) (iRAP methodology, 2013).

Table 10.1. Motorcyclist star rating score

Crash type	Factor	Road attribute risk factor
Run-off score (driver and passenger sides calculated separately)	Likelihood	• Lane width • Curvature • Quality of curve • Delineation • Shoulder rumble strips • Road condition • Grade • Skid resistance
	Severity	• Roadside object • Distance to roadside object • Paved shoulder width
	Operating speed External flow influence Median traversability	
Head-on (loss-of-control)	Likelihood	• Lane width

score		• Curvature • Quality of curve • Delineation • Centreline rumble strips • Road condition • Grade • Skid resistance
	Severity	• Median type
	Operating speed External flow influence Median traversability	
Head-on overtaking score	Likelihood	• Number of lane • Grade • Skid resistance • Differential speeds
	Severity	• Median type
	Operating speed External flow influence	
Intersection score	Likelihood	• Intersection type • Intersection quality • Grade • Street lighting • Skid resistance / grip • Sight distance • Channelisation • Speed management / traffic calming
	Severity	• Intersection type
	Operating speed External flow influence	

Property access score	Likelihood	• Property access points • Service road
	Severity	• Property access points
	Operating speed External flow influence	
Along score	Likelihood	• Facilities for two wheelers
	Severity	• Facilities for two wheelers
	Operating speed External flow influence	

10.5. Enhancing the Star Rating System (SRS) for Motorcyclists

10.5.1 Risk scores of rear-end and sideswipe crashes

Once crash risk factors have been identified and quantified, safety treatment measures may be chosen for consequent implementation based on a rational approach as suggested in Chapter 9. For example, the relative risk of a segregated motorcycle lane for sideswipe crash is 0.43, implying that the likelihood of sideswipe crash for motorcyclists will reduce to 43 % if a segregated motorcycle lane was provided.

This approach is essentially the same as that of the International Road Assessment Programme (iRAP) methodology developed to assess the crash risk for different road users with the view to design countermeasures for safety improvement programmes. In the iRAP methodology, the crash risk is measured by crash scores based on assessing road attributes. The score of a crash type is calculated by multiplying the relative risk value of factors related to the likelihood and severity for that crash type. By embedding the models developed in this study in the iRAP methodology, the risk scores of rear-end and sideswipe crashes for motorcyclists may be determined using the relative risk of contributing factors (see Chapter 9) as identified in Table 10.2, and complement the risk factors of the existing types of motorcycle crashes.

To demonstrate and assess the methodology being proposed, a dataset from Nguyen Tri Phuong Street (see Chapter 5) was used. The traffic characteristics and the observations of rear-end and sideswipe conflicts on this road segment for different time periods from 06:00 am to 09:00 am and from 03:00 pm to 06:00 pm are described in Table 10.3. Consequently, the observed conflicts of each hour (one time period) for six hours were compared with the corresponding estimated risk scores for the same time periods. The results are shown in Tables 10.4 and 10.5. To compare the two different parametric variables, the ranking comparison technique was applied. The method assesses the correlation of the observed conflict frequency with the corresponding estimated risk scores. In this comparison, the estimated risk scores rankings during six hours were compared to the rankings of the same time periods resulted from the observed conflict frequency. This process is conducted in the following three steps (A, B and C).

Step A: Risk score ranking

In this step, the risk scores of rear-end and sideswipe crashes using the likelihood factors were estimated for each hour of six time periods on the road segment considered. These time periods were then ranked according to the estimated risk scores in descending order.

Step B: Observed conflict ranking

In this step, the frequency of rear-end and sideswipe conflicts were observed on the road segment for each hour of six hours. These time periods were then ranked according to the observed conflict frequencies in descending order.

Step C: Ranking comparison

In this step, the time period rankings based on the estimated risk scores were compared to the same time period rankings based on the observed conflict frequency. To determine the level of agreement between these rankings, the Spearman rank correlation coefficient was used. This is a nonparametric comparison measure and therefore appropriate to use for this task. If there is a perfect correlation between two rankings, the value of correlation coefficient is 1.0 and there is no correlation between them if the value of coefficient is 0.0. The Spearman rank correlation coefficient (ρ_s) is calculated as follows:

$$\rho_s = 1 - \frac{6 \sum d_i^2}{n(n^2 - 1)}$$

where,

d_i: is the difference between two rankings for the time period i

n: is the number of time periods ranked (n = 6)

The rankings for each time period are shown in Table 10.4 and the comparison results are shown in Table 10.5. The comparison results reveal that there is a strong correlation between the estimated risk scores with the observed conflict frequency, implying that the risk score measure produces a good estimate of crash potentials for motorcyclists with regard to the data set considered.

Table 10.2. Risk factors contributing to rear-end and sideswipe crashes

<table>
<tr><th>Crash type</th><th>Factor</th><th>Traffic and road attributes</th></tr>
<tr><td rowspan="4">Rear-end crash</td><td>Likelihood</td><td>• Speed
• Speed difference
• Traffic density
• Lateral clearance
• Front distance
• Longitudinal gap
• Road surface condition
• Presence of segregated motorcycle lane</td></tr>
<tr><td>Severity</td><td>• Segregated motorcycle lane</td></tr>
<tr><td>Operating speed</td><td rowspan="2"></td></tr>
<tr><td>External flow influence</td></tr>
<tr><td rowspan="4">Sideswipe crash</td><td>Likelihood</td><td>• Speed
• Speed difference
• Traffic density
• Lateral clearance
• Front distance
• Longitudinal gap
• Lateral gap
• Road surface condition
• Presence of segregated motorcycle lane</td></tr>
<tr><td>Severity</td><td>• Segregated motorcycle lane</td></tr>
<tr><td>Operating speed</td><td rowspan="2"></td></tr>
<tr><td>External flow influence</td></tr>
</table>

Table 10.3. Dataset from Nguyen Tri Phuong Street

Time periods	Traffic volume (motorcycles/hour)	Average density (motorcycles/1000 m^2)	Average speed (m/s)	Rear-end conflicts	Sideswipe conflicts
6:00am-7:00am	3137	74	9.75	9	5
7:00am-8:00am	4297	102	8.72	27	10
8:00am-9:00am	3471	82	9.45	24	14
3:00pm-4:00pm	2971	70	9.91	5	2
4:00pm-5:00pm	3975	90	9.15	22	12
5:00pm-6:00pm	5284	125	7.95	46	15

Table 10.4. Risk score estimates and comparison results

Time period	Risk score estimate (likelihood factor)				Observed conflict frequency			
	Rear-end	Sideswipe	Total	Ranking	Rear-end	Sideswipe	Total	Ranking
6:00am-7:00am	1.4	1.4	2.8	**5**	9	5	14	**5**
7:00am-8:00am	4.0	1.0	5.0	**2**	29	7	36	**2**
8:00am-9:00am	2.1	2.0	4.1	**4**	17	10	27	**4**
3:00pm-4:00pm	1.1	1.0	2.2	**6**	5	2	7	**6**
4:00pm-5:00pm	2.9	2.0	4.9	**3**	22	11	33	**3**
5:00pm-6:00pm	5.6	0.0	5.6	**1**	46	15	61	**1**

Table 10.5. Correlation coefficient

Methodology	Observed conflict frequency
Risk score estimate	1.00**

** Correlation is significant at the 0.01 level

10.5.2 Proposing an enhanced star rating methodology

To provide an enhanced tool for assessing the motorcyclist safety in a motorcycle-dominated traffic environment, the existing iRAP star rating score system may be enhanced by taking into account the risk of rear-end and sideswipe crashes as follows:

$$\text{Motorcyclist SRS} = (\text{Run-off} + \text{Head-on} + \text{Intersection} + \text{Property} + \text{Along} \\ + \text{Rear-end} + \text{Sideswipe})\ \text{Crash Type Scores}$$

(Equation 6.5)

The scores of rear-end and sideswipe crashes are calculated as follows:

$$(\text{Rear-end / Sideswipe})\ \text{Crash Type Score} = \text{Likelihood} \times \text{Severity} \times \text{Operating speed} \\ \times \text{External flow influence}$$

(Equation 6.6)

The risk factors that contribute to the likelihood and severity of rear-end and sideswipe crashes are identified in Table 10.2.

10.5.3 Testing, Outputs and comparisons

To compare the outputs between the existing iRAP star rating system and a consequent iRAP star rating system based on the models developed in this study, dataset from five homogeneous road sections were chosen randomly from five divided roads in the city of

Danang in Vietnam as described in Table 10.6 and Table 10.7 and then analysed. An example of calculating the star rating score using the enhanced iRAP SRS is shown in Appendix D. Table 10.8 shows that the existing iRAP SRS produces the same star rating scores for five locations while star rating scores produced from the enhanced iRAP SRS had the same trend with actual crash history.

Table 10.6. Geometry characteristics of road segments

Location	Road name	Road length (m)	Number of lanes	Lane width (m)
1	Nguyen Van Linh	2170	2	4
2	Bach Dang	2542	4	3.75
3	Duong 2-9	3377	3	3.5
4	Nguyen Tri Phuong	1295	2	3.5
5	Dien Bien Phu	2700	4	3.5

Table 10.7. Traffic characteristics of road segments and historical crash data

Location	Volume (vehicles/day)	Density (vehicles/1000m^2)	Average speed (m/s)	Crash records (2008-2015) (serious and fatal motorcycle – motorcycle crashes)	
				Rear-end	Sideswipe
1	59704	89	9.68	21	5
2	41621	68	9.99	9	2
3	49706	72	9.83	16	4
4	61402	94	9.48	27	7
5	78945	76	9.19	35	9

- Historical crash data collection source: Danang Department of Transport

Table 10.8. Comparison results between existing and enhanced iRAP SRS system

Location	Existing iRAP SRS system	Enhanced iRAP SRS system	Crash history
1	0.76	1.28	26
2	0.76	1.09	11
3	0.76	1.20	20
4	0.76	1.37	34
5	0.76	1.47	44

10.5.4 Verifying the enhanced iRAP SRS methodology

To test the performance of a subsequent iRAP SRS system, the Star Rating Score of the 5 road sections were compared with the actual crash data collected at those road segments and with the crash frequency predicted by the Highway Safety Manual (HSM) methodology (AASHTO, 2009). This test process is conducted in the following three steps (A, B, C and D).

Step A: Enhanced iRAP SRS methodology ranking

In this step, the Star Rating Score (SRS) of each road segment was calculated by the consequent iRAP Star Rating Score system. These locations were then ranked according to the values of SRS in descending order.

Step B: HSM methodology ranking

In this step, the average yearly crash frequency of each road segment was predicted using the methodology proposed by the Highway Safety Manual (HSM) methodology (AASHTO, 2009). These locations were then ranked according to the predicted crash frequency in descending order.

Step C: Actual crash ranking

In this step, the road segments were ranked according to the average actual annual crash frequency in descending order. The average yearly crash frequency was determined by dividing the total number of historical crashes by the number of years collected. The actual crash data were gathered over the period from 2008 to 2015 of each 1000m road length for this test.

Step D: Ranking comparison

In this step, to determine the level of agreement between these rankings, the Spearman rank correlation coefficient was used.

The outputs of methodologies and the corresponding rankings for road segments are shown in Table 10.9 and the comparison results are shown in Table 10.10. The comparison results reveal that there is a strong correlation between the outputs of the enhanced iRAP star rating methodology with the actual historical crash data, implying that the enhanced iRAP methodology seems to produce enhanced results in comparison to the HSM methodology. However, a larger data set (which could not be collected during the course of this PhD programme because of its resource constraints) would be needed to increase the certainty of this finding.

Table 10.9. Outputs of methodologies and rankings for road segments

Locations	Enhance iRAP SRS		HSM methodology		Actual historical crash	
	SRS	**Ranking**	Crash frequency	**Ranking**	Crash frequency	**Ranking**
1	1.3	**3**	0.6	**2**	3.3	**3**
2	1.1	**5**	0.4	**4**	1.4	**5**
3	1.2	**4**	0.5	**3**	2.5	**4**
4	1.4	**2**	0.6	**2**	4.2	**2**
5	1.5	**1**	0.8	**1**	5.5	**1**

Table 10.10. Spearman rank correlation coefficient

Methodology	Average actual historical crash
Enhanced iRAP SRS	1.00**
HSM methodology	0.97**

** Correlation is significant at the 0.01 level

10.6. Conclusion

This chapter suggested an application of the developed models in determining the risk scores of rear-end and sideswipe crashes for motorcycles at a specific site based on assessing the relative contribution of risk factors on crashes. Further application of this is to enhance the iRAP star rating system for motorcyclists by integrating the risk scores of these two crash types into the existing iRAP SRS system. The outputs of the enhanced iRAP star rating methodology produced satisfactory results and there were consistent with historical crash data and therefore show the potential of the models developed for inclusion in the existing iRAP star rating system.

CHAPTER 11

DISCUSSION

11.1. Introduction

This chapter presents a discussion of the findings of this study with regard to the modelling approach, the model development process, the effect of the contributing factors included in the developed models on crash risk, the potential application of the proposed concept of the Conflict Modification Factor in road safety analysis, and the applications of the developed models in enhancing the existing iRAP motorcyclist star rating methodology and selecting appropriate countermeasures to improve motorcyclist safety.

11.2. Modelling Approach Adopted in This Study

To develop models to assess the risk of rear-end and sideswipe crashes for motorcyclists, this study adopted the traffic conflict technique which is based on determining the occurrence of rear-end and sideswipe conflicts instead of using the traditional approach which is based on analyses of historical crash data. The adoption of the traffic conflict technique was chosen based on the statistical relationship between the frequency of conflict and crash events and their similar causal mechanisms as stated in Section 9.1.2.

Therefore, by using the surrogate measure approach, the crash risk may be assessed from the determination of the occurrence of conflicts which have the characteristics of crashes, but with no actual crash results (Hydén, 1987; Svensson, 1992; Archer, 2004; Ismail, 2010; Laureshyn, 2010).

From the validation results, as stated in Chapter 8, it was found that the estimate of rear-end and sideswipe conflicts were strongly correlated to the actual crash data and the developed models produced more reliable results compared with the existing methodologies found in the literature. The former suggests a verification of the assumptions made in this Thesis and the latter that the produced models offer an enhancement over other existing methodologies. It may therefore be suggested that the use of the traffic conflict technique in road safety analysis, such as that presented in this Thesis, may be an appropriate approach to address issues found in most LMICs. These issues include that of obtaining a reliable historical crash data for road safety analysis and taking into account explicitly the contribution of movement characteristics of road users to the crash potential. The traffic conflict technique is based on the observation of traffic events in the field, therefore the actual behaviour of road users may be captured to assess their effects on crash risk.

11.3 Traffic Conflict Technique Verification

Road safety is one of the most essential aspects of transport engineering. The planning, design, and maintenance of transport facilities should consider the reduction of crashes when designing or evaluating alternative designs. Since crash data analysis is a direct measure of road safety studies, the development of crash prediction models is able to give policy-makers, planners and traffic engineers a clear insight into past, current and future safety. Therefore, crash prediction models play a very important role in road safety study and need to be carefully examined to ensure their accuracy and reliability. However, most crash prediction models are statistically-based methods requiring significant efforts on the reliability and availability of crash data (see section 2.1.1). Therefore, it is necessary to apply surrogate measure instead of using crash data in countries where good crash data history are not available. Compared to crashes that are rare and random events, traffic conflicts are considered to be a more frequent and share the similar causal mechanisms to crashes. The traffic conflict techniques have been applied widely in road safety analysis and have been validated in a number of studies (see section 2.1.2).

The key requirement for using conflict as a surrogate measure is that the frequency of conflict is strongly associated with the frequency of crashes. That is, if a certain number of conflicts are observed, an accurate estimate of the number of crashes to occur will be obtainable. This is directly corresponding to the motivation for using traffic conflict measure: instead of modelling or evaluating the relatively small number of crashes observed, the relatively larger number of conflicts can be used to attain an improved assessment of traffic safety. A strong association will guarantee that an analysis using conflicts will not depart significantly from the results of an analysis using crashes only. The association between crashes and conflict can be measured by the ratio between them. As stated in Section 2.1.2, the logical and statistical relationship between the frequency of conflict and crash has been validated in a number of studies. According to the research conducted by Gettman *et al.* (2008), they found that the ratio of traffic conflicts to actual crashes were 20,000 to 1.

The relationship between the frequency of crash and conflict is critical for evaluating surrogate measures. A constant crash-to-conflict ratio is an ideal situation where risk estimation using either crash alone or in combination with conflict will lead to identical results. Even when the constant ratio is not satisfied, a strong linear relationship between crash and conflict will also provide valuable information about crash risk. To verify the traffic conflict technique used in this research, two tests were conducted:

- Test 1: Comparing the frequency of conflicts estimated by this study with the frequency of conflicts observed directly in the field. To record the conflicts in the field via video recordings, this study applied guidelines presented in the Observers Manual published by Federal Highway Administration (Parker and Zegeer, 1989). According to this guideline, conflicts were defined as the occurrence of evasive vehicular actions and were recognisable by braking and/or weaving manoeuvre of motorcycles. Braking is usually observed as brake–light indications, however, some motorcycles are driven with inoperative brake lights. A noticeable diving of the vehicle or squealing of tyres in the absence of brake lights is acceptable evidence of an evasive manoeuvre. This test illustrated that the agreement level between the estimated and observed conflicts reach 89.8% (see section 8.2).
- Test 2: Comparing the frequency of conflicts estimated by this study with the real crash data. The full historical crash data are not available in Vietnam, therefore this study used the data of serious and fatal motorcycle-motorcycle crashes only. This test revealed that there was a strong correlation between estimated conflicts and actual crashes (see section 8.3).

Although these two tests may verify the traffic conflict technique used in this study, the data used for these tests were limited from ten roads in the city of Danang in Vietnam. In addition, the crash data used in the test processes were serious and fatal motorcycle-motorcycle crashes only. Therefore, to validate the traffic conflict adopted in this study for a wider application, there is need of a more comprehensive historical crash data to establish the statistical relationship with conflict frequency (e.g. the ratio of conflicts to crashes). Moreover, the validation process should be used more data collected from various cities and countries with similar traffic characteristics. However, such those tasks would require significant resources and were beyond the scope and duration of this study.

11.4. Model Development Methodology

11.4.1 The model development process

As stated in Section 3.5, the models were based on the discrete choice model (e.g. logistic regression model) and the traffic conflict technique using the theory of probabilities. The risk of crashes was estimated from the probability of conflicts which, in turn, were determined by the probabilities of motorcyclists' manoeuvre behaviour that may potentially result in the occurrence of conflicts.

According to the proposed methodology, the crash risk is based on assessing the movement behaviour of motorcyclists and traffic conflict events, which are observed in real time in the field, and therefore data can be collected in a short time period by video recording. The major advantages of the video recording method are its low cost and the ability to capture the trajectories of all vehicles in the traffic stream. In addition, this is an objective observation method that is not affected by the observers and researchers, and a video file can be reviewed repeatedly to ensure the quality of the information extracted. However, the main disadvantage of this method is that it is extremely time-consuming. For example, to extract vehicles' trajectories from an hour's video file requires approximately 200 person-hours (Lee, 2007). Difficulties in this methodology are that a good computer software and well trained observers or researchers are required to collect, extract and process all data need from video files. Both the technical specifications of the video camera and the software used to analyse the data may affect the entire modelling process and this needs to be considered if the methodology developed reaches the stage of full commercial implementation.

The data used for the models fitting and validation process were collected from ten road segments from various roads in the city of Danang in Vietnam. It should be appreciated that a more comprehensive data set comprising road segments different from the above and preferably collected from other cities or countries with similar traffic characteristics would be required for a model with a wider application. However, such a task was beyond the scope of this study, which sought to demonstrate the development process of the model and its testing, and would require significant resources which were not available during this PhD programme.

11.4.2 The success of the developed crash risk models

To validate the success of rear-end and sideswipe crash risk models developed in this study, three tests were conducted: a) assessing the goodness-of-fit, b) field validation, and c) literature validation tests.

a) Test 1: The purpose of assessing the goodness-of-fit of the developed model is to test how effective the model is in describing the outcome variable. For this test, the data set from Nguyen Van Linh street was used and the result indicated that the overall agreement between the predicted to the observed values reaches 94.0 %, implying that the developed model captures satisfactory the movement behaviour of motorcyclists.

b) Test 2 was conducted to verify the success of the developed models in the real world by comparing the predictive conflict frequency produced by the developed models with the actual conflict frequency observed in the field. For this test, a data set from Nguyen Tri Phuong Street was used. The field validation results showed that the agreement between the estimated and observed conflict frequency reaches 89.8 %, implying that the developed crash risk models produce good estimates for both rear-end and sideswipe conflict frequency.

c) Test 3 was conducted for two purposes: the first purpose was to enable a correlation of the crash potentials produced by the proposed models with actual crash history. The second purpose was to identify any correlation between the output of the proposed models and existing methodologies found in the literature. For this task, a data set from ten Streets in Danang was used. The results were as follows.

   - For the first purpose, the test result illustrated that the crash risk estimated from the proposed models was strongly correlated to the historical crash data as the value of correlation coefficient between them was 0.98, implying that the proposed models produce most satisfactory crash risk estimates.
   - For the second purpose, compared with the Highway Safety Manual (HSM) methodology (AASHTO, 2009) and the International Road Assessment Programme methodology (iRAP, 2013), the methodology developed in this study presents the strongest correlation with the actual crash history. The correlation coefficient value for the proposed methodology is 0.98 while those of for the HSM methodology and iRAP methodology are 0.91 and 0.87 respectively. This implies that the proposed models produce consistent and slightly better estimates compared with the existing models found from the literature.

From the results of three validation efforts it could therefore be suggested that the outputs of the developed models are reliable and may therefore be used to determine hazardous road locations associated with higher crash risk, in order to develop countermeasures to improve motorcyclist safety. It could also be suggested that the developed methodology may have a number of applications in road safety analysis in motorcycle-dominated traffic environments in low-income and middle-income countries where the under-reporting of accidents and the poor quality of historical crash data is a major drawback in making decisions of good quality.

11.5. The Importance of Data

11.5.1 The quantity of data

The data used for model fitting and validation was the vehicles' trajectory extracted from the traffic video recordings in real time. The trajectories of vehicles were observed at discrete points in time with intervals of 0.5 second. Therefore the number of observations obtained from 6 hours of traffic recording at road segments in this study was likely to capture a wide range of traffic conditions (e.g. various traffic density conditions, various level of operating speeds, various relative distances and relative speed between the subject motorcycles and surrounding vehicles, various movement behaviours) for modelling purposes.

In addition, the developed models investigate the effect of driving conditions with respect to the surrounding vehicles on the movement behaviour of the subject motorcyclist. In other words, the presence of neighbouring vehicles on the road directly affects the subject drivers' decisions for their movement choices. Therefore, one observation may present one traffic condition, and the 535 observations of vehicles' trajectories in real time used to fit the model, may mean that 535 various traffic conditions were captured to investigate their effects on the manoeuvre behaviour of motorcyclists.

For all the above reasons, and within the resource constraints of this study, it was felt that the data used for this study could satisfy an empirically driven sampling process. It could be argued that a robust statistical sample could produce different results. It is felt however that these would not change the overall approach followed but possibly the various coefficients determined from regression analysis. However, there are reasons to believe that the enhancement of the coefficients would be probably small as already the various tests of the models showed that the models perform at least satisfactorily. Moreover, the data collection process could be improved by selecting a video recorder with high resolution so that the trajectories of vehicles could be extracted from these video files with higher accuracy. In addition, the computer software used to track the vehicle trajectories could offer more satisfactory accuracy of the data computed.

11.5.2. The number of samples used for the logistic regression analysis

The coefficients of the proposed manoeuvre model were estimated using 2675 observations of vehicles' trajectories (535 observations of 108 subject motorcycles and 2140 observations of 432 influential vehicles) in the field. Based on the requirement of minimum samples used for the statistical process of the logistic regression analysis, the 535 samples used to estimate coefficients of the logistic regression model in this study were considered sufficient to achieve a reliable result (Peduzzi *et al*, 1996).

Peduzzi *et al*. (1996) proposed an equation to determine the minimum number of samples for logistic regression as follows:

$$N = \frac{10 \times k}{p}$$

(Equation 11.1)

where, p is the smallest of the proportions of the following manoeuvre or the swerving manoeuvre cases in the total of observations, k is the number of independent variables included in the model.

For this study (k = 7 variables and p = 0.39), the number of 535 observations used to estimate coefficients are much greater than the minimum number of samples required for logistic regression analysis (N = 10 * 7 / 0.39 = 179 observations). According to Peduzzi *et al.* (1996), although the number of samples used is much larger than the required minimum samples, the estimate results are not significantly affected. Therefore, if data are collected from more road segments, which means more than 535 observations will be used to estimate the coefficients of the models, this will not significantly affect the estimated results. For this reason, although more data are always desirable, it could be stated that the data used in this study seem to be satisfactory.

11.6. Contributing Factors Included in the Models

Factors contributing to the potential of crashes that were assessed in this study included: operating speed, speed difference, front distance, longitudinal gap, lateral clearance, traffic density, and road surface condition. The non-lane-based movements were considered via the lateral clearance and the longitudinal gap variables included in the developed models. For the developed models and the data sets used, it was found that the effect of these contributing factors on motorcycle crash risk was as follows.

11.6.1 The operating speed factor

The operating speed of motorcycles was found to be the most significant factor contributing to both rear-end and sideswipe crash risk. This factor affected both the manoeuvre behaviours of motorcyclists and the threshold safety distance of a motorcycle. It was found that the crash potentials increase correspondingly with the greater values of motorcycles' speed and the crash risk increases dramatically after a value of 30 km/h onwards. Although it seems that no study has to date investigated the effect of motorcycles' speed on rear-end and sideswipe crashes in motorcycle-dominated traffic environments, the effect of this factor on the overall crashes (e.g. total crash injuries or fatality), as found from previous studies, showed a similar trend (Taylor *et al.,* 2000; Elvik *et al.,* 2009; iRAP, 2013).

11.6.2 The speed difference factor

The difference in speed of the subject motorcycle with the front vehicle (called speed difference) was found to significantly affect the manoeuvre behaviour of the motorcyclists. It was found that motorcyclists tend to choose swerving manoeuvres when their speeds are higher than that of the front vehicles and this leads to an increase in the sideswipe crash risk. It was also found that when the speed of the subject motorcycle was less than 5 km/h compared with the front vehicle, the risk of both rear-end and sideswipe crashes was insignificant. In addition, the rear-end crash risk decreases and the sideswipe crash risk increases significantly if motorcycle's speeds were higher by 2.5 km/h than that of the front vehicles. The effect of this factor on crash risk was investigated by a number of researches but it appears that a very limited number of studies, if any, has focused on rear-end and sideswipe crashes and motorcycle-dominated traffic environment that were considered in this study.

However, the overall influence trend was found to be similar with that in other studies (Nilsson, 2004; Elvik *et al.,* 2009).

11.6.3 The front distance factor

The gap between the subject motorcycle and its front vehicle (called the front distance) was found to be a significant factor contributing to the manoeuvres of motorcyclists. It was found that motorcyclists were more likely to choose a swerving manoeuvre if the gaps maintained with the front vehicles become shorter and led to an increase in sideswipe crash risk. The rear-end crash risk was found to increase with the increase of the front distances but this risk decreased if the front distances were more than 3.0 m. This factor was considered in this study to investigate the effect of the unique movement of motorcycles (e.g. maintaining a short gap with the front vehicle) on rear-end and sideswipe crashes in motorcycle-dominated traffic environments, and it appears that no study, at least from those included in the literature review for this work, has focused on this aspect.

11.6.4 The longitudinal gap factor

The longitudinal distance between the subject motorcycle and the vehicle following behind on the left or right (called longitudinal gap) was found to influence the movement behaviours of motorcyclists. It was found that motorcyclists preferred to choose a swerving manoeuvre as the longitudinal gaps increased. This factor was not found to significantly contribute to the rear-end crash risk and not to affect the sideswipe crash risk if it was greater than 3.5 m. This factor was considered to investigate the effect of the non-lane-based movements of motorcycles on rear-end and sideswipe crashes in motorcycle-dominated traffic environments, and no study, at least from those included in the literature review for this work, has focused on this aspect.

11.6.5 The lateral clearance factor

The lateral clearance distance (on the left or right) of the front vehicle (called lateral clearance) was found to have a significant impact on the movement behaviours of motorcyclists. This factor was included in the models to take into consideration the non-lane-based movement characteristics of motorcyclists. It was found that motorcyclists were more likely to choose a swerving manoeuvre as the lateral clearance increased and this led to an increase in the sideswipe crash risk and a decrease in the rear-end crash risk. This factor was used to investigate the effect of the non-lane-based movements of motorcycles on rear-end and sideswipe crashes in motorcycle-dominated traffic environments, and no study, at least from those included in the literature review for this work, has focused on this aspect.

11.6.6 Traffic density factor

It was found that the rear-end crash risk increases with increasing values of traffic density and reaches a peak at 150 motorcycles/1000 m^2 and then slightly decreases. It was also found that the sideswipe crash risk increases as the traffic density increases and reaches a peak at 100 motorcycles/1000 m^2 and then decreases slightly to approach zero when the density is 150 motorcycles/1000 m^2.

According to six traffic density condition levels (see section 9.1.3), it was found that both rear-end crash and sideswipe crashes are of low risk in the “Very high traffic density condition” (e.g. nearly congestion). The sideswipe crash approaches the highest risk in the “Low traffic density condition” while the greater the traffic density the higher the rear-end crash risk. No study, at least from those included in the literature review for this work, has investigated the effect of this factor on rear-end and sideswipe crashes in motorcycle-dominated traffic environments.

11.6.7 The road surface condition factor

The wet and dry road surface conditions were investigated their effects on crash risk. It was found that the wet road surface condition increases the risk of both rear-end and sideswipe crashes. Although, the effect of this factor on crash risk was investigated by a number of researchers but no study found from the literature focused on two specific crash types and the particular traffic environment considered in this study. However, the overall effect trend of this factor on crashes was found to be similar with that in other studies (Haworth *et al., 1997*; Shankar and Mannering, 1996; Elliott *et al., 2003*; Haque *et al.,* 2009).

11.7. The New Concept of Conflict Modification Factor

This study proposed a new concept, called the Conflict Modification Factor (CoMF), to use as a surrogate measure to the Crash Modification Factor (CMF) (section 9.1) in road safety analysis. CoMFs represent the relative change in the conflict frequency due to the change in one specific condition while all other conditions remain constant and CMFs represent the relative change in the crash frequency. Therefore, CoMF may be used as a surrogate measure to CMF in road safety analysis due to their statistical relationship and similar causal mechanism (section 9.1.2).

The innovative feature of this approach is that the relative risk value of risk factors can be determined using conflict data instead of crash data. Therefore, CoMFs can be used in before and after studies by observing the conflict frequency before and after a particular treatment measure implemented instead of waiting for sufficient years of crash data to build up. Hence, the effectiveness of a particular countermeasure already implemented can be assessed in a short time by using CoMFs compared with using crash data.

The statistical relationship between crashes and conflicts is the key for proposing this new concept. Conflicts are less severe than crashes, and their frequency of occurrence is expected to be higher than crashes. It can also be shown that if there is a perfect relationship (e.g. constant crash-to-conflict ratio), the relative risk values for using crashes alone and combining crashes and conflicts will be identical. However, according to Guo *et al.* (2010), the combined analysis will provide a more accurate estimation due to tighter confidence intervals. Therefore, CoMFs can be used alongside crash data for before and after studies, and the result would be expected more accurately.

11.8. Methodology to Enhance the Existing iRAP SRS for Motorcyclists

This study proposed a methodology to enhance the existing iRAP star rating system for motorcyclists by integrating the rear-end and sideswipe crash risk into the star rating system (see Chapter 10). The enhanced model is likely to cover most crash types of motorcycles in a motorcycle-dominated traffic environment of urban roads and therefore the crash risk for a certain road segment would also be captured more satisfactorily leading to more appropriate countermeasures to improve motorcyclist safety.

In the enhanced model, data associated with the new risk factors (e.g. front distance, lateral clearance, longitudinal and lateral gaps) cannot be collected using the current iRAP survey vehicle. Therefore, to collect all required data for the enhanced model, it could be suggested that the current iRAP vehicle should be instrumented with an upgraded data collection system consisting of a computer that receives and stores data from a network of sensors distributed around the vehicle. Sensors may include an accelerometer box to obtain longitudinal and lateral kinematic information, a headway detection system to provide information about the leading or following vehicles, and a GPS sensor to record the vehicle's location. It appears that this new system could potentially cost about 3,000 to 4,000 USD (source: roadtraffic-technology.com) but the actual cost and the integration of the system with the current iRAP configuration should be systematically developed. Similarly to the iRAP methodology, the required data should be collected for each 100 metre segment of all roads.

By comparing the proposed methodology with the existing iRAP SRS methodology, it was found that a consequent iRAP methodology could produce at least satisfactory outputs. It could therefore be suggested that the rear-end and sideswipe crash risk models developed in this study have the potential for inclusion in the iRAP star rating system for motorcyclists. However, the proposed methodology to enhance the current iRAP star rating system should be subject to more testing before further implementation. In addition if the modelling approach developed in this study were adopted by the iRAP methodology, it would facilitate significantly its introduction to a large number of countries with traffic conditions similar to Vietnam. Such countries are those of Southeast Asian in which the number of killed and serious injuries (KSI) is 230,652 per year and their cost is estimated to be approximately US$ 15 billion.

11.9. Cost Consideration

11.9.1 Cost of Variable Message Signs

Variable Message Signs (e.g. changeable speed limit signs, changeable gap warning signs, changeable road surface condition warning signs) are more expensive than ordinary traffic signs. According to cost estimates published by the US Research and Innovative Technology Administration (RITA), variable message display signs cost between 3,200 and 4,400 USD, while dynamic (e.g. fully automated) message signs cost between 44,000 and 111,000 USD. For example in Vietnam, a variable speed sign board with the text 'Your speed is XX kilometres per hour' costs 10,469 USD (2014 prices). The price includes the board with the text, the display with light diodes to show speeds, a radar on the top of the board and the trailer upon which the board is mounted. The above price is considered affordable.

An alternative measure for enforcing motorcyclists to maintain safety distances with the front vehicles may be chevrons painted on the road surface. In a project conducted by the iRAP in Vietnam in 2009, estimate costs of this treatment were 4,670 USD per carriageway kilometre. However, in order to choose an appropriate safety treatment measure, a cost analysis of various countermeasures should be considered.

11.9.1 Cost of Motorcycle Lanes

As stated in section 9.2.4, providing a separate motorcycle lane to prevent crashes between motorcycles and heavier vehicles and to reduce swerving/weaving manoeuvres and erratic movements is an efficient measure to improve motorcyclist safety. Separate motorcycle lanes can be provided by "painted logos only on-road" or "construct on road" or "segregated". In a project conducted by the iRAP in Vietnam in 2009, estimate costs for building motorcycle lanes per one kilometre by “painted logos only on-road”, “construct on road” and “segregated” were 5,241 USD, 491,317 USD and 335,883 USD respectively. The above prices are considered affordable.

11.10. Application in Vietnam

This research was funded by the Government of Vietnam to address the practical problem of motorcyclists safety in urban areas of Vietnam focusing on the city of Danang. It is felt that this Thesis achieved this goal as it offers an enhanced understanding of factors affecting the motorcyclists safety in the cities of Vietnam with similar traffic characteristics with those of Danang. In addition, the research has suggested road safety countermeasures for immediate pilot implementation so that a more generalised approach to planning urban roads may be ultimately facilitated. It is believed that the implementation of the findings of this study will have a significant impact on the reduction of road crashes and consequently of road safety costs. Furthermore the work reported herein may be considered as a first stage towards a more systematic analysis of motorcyclists safety issues in Vietnam and capacity building actions with impacts not only in Vietnam but in the South East Asia region and even beyond.

11.11. Policy Implementation in Vietnam

Notwithstanding the value of robust scientific findings, it is important to consider that legislation and enforcement are complementary tools which together with engineering approaches can reduce road traffic crashes, injuries and deaths effectively and improve the movement behaviour of motorcyclists. The most positive changes to the manoeuvre behaviour of motorcyclists happen when road safety legislation is supported by strong and sustained enforcement, and where the public is made aware of the reasons behind the new law and the consequences of noncompliance. To this end, using the findings of this research, the following potential policies could be suggested for Vietnam:

- Lane-based movement legislation: This research demonstrated that the non-lane based movement of motorcycles has a significant effect on road safety. Therefore setting a new legislation to enforce motorcyclists to follow lane disciplines and lane markings would assist in reducing swerving/weaving manoeuvres and erratic movements of motorcycles.
- Minimum gap regulation: Keeping a short distance with the front vehicle will potentially result in rear-end collisions. Therefore, setting and enforcing motorcyclists to keep a minimum gap with the front vehicles could contribute to the reduction of rear-end crashes.
- Motorcycle segregated lane legislation: This research has shown the value of providing segregated lanes for motorcycles in increasing road safety. Therefore, setting a legislation or even guidelines to separate motorcycles from other transport modes, not only could improve motorcyclist safety but also optimise land use planning and traffic management.
- Road safety infrastructure standards: This research demonstrated that road designs and traffic condition features have a significant impact on motorcycle crash risk. Therefore, setting minimum standards for new road designs and existing road maintenance policy seems to be another need to be addressed by legislation to enhance motorcyclist safety.
- Speed limit legislation: The research has shown that setting and enforcing speed limits is an important step in reducing motorcycle crashes. It is also found that motorcycle

crash risk increases significantly when the speed is higher than 35 km/h, therefore it would suggest that the urban speed limit for motorcycles in Vietnam should be less than or equal to 35 km/h, in line with best practice. Rigorous enforcement of speed limit legislation is essential to make it truly effective. Without ongoing and visible enforcement of speed legislation, the potential impact of speed legislation to improve motorcyclist safety remains vastly unattained. It is important that local authorities in Vietnam Government not only have the legal authority to reduce national limits, but also to manage local speeds according to particular road situations and in various traffic density conditions with other traffic calming or speed management policies.

- Changes in the model split of travel: Compared with riding a motorcycle, public transport has a considerably lower level of risk (see section 3.7). Therefore, shifting to public transport may be a very effective strategy of the authorities to reduce crash risk of private transport mode such as motorcycle. Several management policies cause shifts from motorcycles to public transport mode by making public transport mode more attractive or by increasing the cost of motorcycle use. For example, encouraging funding decisions that strengthen public transportation and providing incentives to support a strong network of public transportation options which connect housing and jobs as well as improve access to healthy foods, medical care, and other services.

11.12. Limitations of this Study

11.12.1 Limitations related to data collection

The methodology used to collect data for this study was video recording, and the data collection process was conducted during daytime and under clear weather condition in order to achieve good visibility for obtaining high quality video images. The effect of night-time or various weather conditions on the manoeuvre behaviour of motorcyclists was not therefore considered. These factors may affect the behaviour of motorcyclists but it would seem likely that they would have an insignificant influence on the models developed in this study that focused only on the normal driving conditions.

In addition, the traffic surveys were conducted on two weekdays (on 21 and 22 August 2014). The effect of varying traffic condition within a week (weekday and weekend days) or month on the movement behaviour of motorcyclists was not captured in the data set. Although this may have an influence on the result, it would seem likely that this effect would have an insignificant as the traffic conditions do not vary significantly throughout the year (DoT, 2013).

Due to the limited area that a video recorder is capable of capturing, the lengths of road segments observed were 40.0 m. Therefore, the behaviour of the subject motorcyclist for a longer journey was not captured. However, it would seem unlikely that this would have a significant effect on the model development process but could affect the accuracy of the models.

11.12.2 Risk factors considered in the models

The occurrence of a road crash is the result of a series of traffic events effected by a large number of risk factors related to the components of the traffic system that include the vehicles, the drivers and the overall road environment. This study investigated the effect of contributing factors related to the traffic conditions and the road environment on the movement behaviour of motorcyclists and their crash risks. Other factors related to motorcyclist characteristics that may affect the rider’s behaviour such as their ages, gender, knowledge and experience, alcohol or drug consumptions, and motorcycle capabilities were not included in the proposed models. In most cases, this information was not available and cannot be directly measured from vehicles' trajectory data in real time, therefore they were not considered in the study and these limitations will be addressed in proposals for future works.

11.13. Summary

In summary, the developed methodology is capable of estimating the risk of rear-end and sideswipe crashes which are two major crash types associated with the non-lane-based movement behaviour of motorcyclists in motorcycle-dominated traffic environments. This filled in a significant gap in motorcycles road safety in these particular traffic conditions that had not been considered in previous studies to date. The developed methodology could provide an invaluable tool to assess and improve motorcyclist safety and it could potentially have an important contribution to saving a large part of the tens of thousands of human lives that are lost every year in South and South East Asia and ultimately help in both road safety management and traffic management in developing countries such as Vietnam.

CHAPTER 12

CONCLUSIONS AND FUTURE WORK

12.1. Conclusions

This study developed a new methodology and new models for assessing the potential of motorcycle crashes and selecting countermeasures to improve motorcyclist safety in a motorcycle-dominated traffic environment of urban roads. The innovative features of this research are that the non-lane-based movements of motorcycles were captured to evaluate their contributions to crash risk and a new concept - that of the Conflict Modification Factor (CoMF) - was proposed to use as a surrogate measure to assess the relative contribution of risk factors to crashes. In addition, a methodology was also developed to enhance the existing iRAP star rating system for motorcyclists. The developed models were fitted and validated using data collected from urban road segments in the city of Danang in Vietnam.

The following conclusions may be drawn from this study.

1. The new models developed in this study provide a good estimate of both the rear-end crash and sideswipe crash risks for motorcyclists in a motorcycle-dominated traffic environment of urban roads.

2. The outputs from the developed models can detect hazardous traffic conditions associated with higher motorcycle crash potentials and hazardous road segments and can therefore identify appropriate counter measures to improve motorcyclist safety.

3. The crash risk models developed in this study are the first of their kind in Vietnam and probably in Southeast Asia regions, in terms of the methodology used and the results achieved. The new findings from the developed models have shown that the rear-end and sideswipe crash risk of motorcyclists are associated with operating speed, speed difference, traffic density, front distance, longitudinal gap, lateral clearance and road surface condition were found to contribute to the risk of rear-end and sideswipe crashes. Specifically, the effects of these factors on motorcycle crashes were as follows:

   3.1. The operating speed has a significant contribution to both rear-end crash and sideswipe crashes; the higher the speeds of vehicles the higher the rear-end and sideswipe crash risk.

   3.2. The speed difference has a significant contribution to the sideswipe crashes but affects insignificantly the rear-end crash risk; the rear-end crash risk decreases if the speed differences are greater than 2.5 km/h; the higher the speed difference the higher the sideswipe crash risk; and the sideswipe crash risk increases significantly if the speed difference is higher than 2.5 km/h.

   3.3. The traffic density affects significantly crash risk. Under very high traffic densities (e.g. near congestion), both rear-end and sideswipe crashes present a low risk but this situation is not desirable as vehicles cannot move in the traffic. The lower the traffic density the higher the sideswipe crash risk while the higher the traffic density the higher the rear-end crash risk.

   3.4. The front distance has a significant contribution to sideswipe crashes and it affects insignificantly the rear-end crash risk.

      i) The shorter the front distances, the higher the sideswipe crash risk;

ii) The rear-end crash risk increases slightly with the increase of the front distances and decreases slightly when the front distances are 3.0 m or higher.

3.5. The longitudinal gap has a significant contribution to the sideswipe crashes but affects insignificantly the rear-end crash risk; the shorter the longitudinal gaps the higher the sideswipe crash risk.

3.6. The lateral clearance has a significant contribution to rear-end crashes while its influence on sideswipe crashes is less but still significant; the higher the lateral clearances the lower the rear-end crash risk while the higher the lateral clearances the higher the sideswipe crash risk.

3.7. With regard to the road surface conditions, it was found that both the rear-end and sideswipe crash risk increase when the road surface is wet.

4. The new concept of the Conflict Modification Factor (CoMF) was proposed in this study to determine the relative risk values of factors contributing to crashes. The innovation of this concept is that CoMF can be determined by using conflict frequency data instead of the historical crash data required by conventional methodologies. The usefulness of CoMF is that it can be used to assess the effectiveness of a particular countermeasure by observing the conflicts in a short period of time to enable comparisons before and after implementing a particular countermeasure instead of waiting for sufficient years of crash data to build up. Therefore, CoMF would be an efficient tool in road safety assessment to overcome the under-reporting or unavailability of historical crash data in most LMICs. Specifically, CoMFs can be used in road safety analysis for the following purposes:

i) To assess the crash risk of a particular site: As CoMFs are used to assess the difference in conflict frequency between the base conditions and the existing conditions, the CoMF can be multiplied with a conflict frequency of base conditions to estimate the average conflict frequency for a specific site under the existing conditions;

ii) To select an appropriate countermeasure for a particular site: A CoMF may be used to assess the difference of conflict frequency before and after implementing a countermeasure; therefore the most appropriate countermeasure may be chosen as part of a treatment programme.

5. The developed crash risk models and the proposed CoMFs identified several potential countermeasures to improve motorcyclists safety. These are:

   i) installing changeable speed limit signs;
   ii) installing changeable gap warning signs;
   iii) installing changeable road surface condition warning signs;
   iv) Providing segregated motorcycle lanes.

6. The proposed methodology to enhance the current iRAP star rating system for motorcyclists seems to produce results consistent with historical crash data and subject to more testing, the methodology may be considered for full implementation. As the methodology of this study could be adopted by the iRAP star rating system, it would facilitate significantly its introduction to a large number of countries with traffic conditions similar to Vietnam such as those in Southeast Asia countries and ultimately save lives and reduce economic losses resulting from motorcycle crashes.

7. The proposed methodology in this research enables a better understanding of the influence of the non-lane-based movement characteristics of motorcycles on crash risk and particularly in LMICs where motorcycles are the predominant mode of urban transport.

8. The important contribution of this research is to enhance an understanding of the effect of risk factors on crash risk for motorcyclists in a motorcycle-dominated traffic environment and countermeasures may therefore be subsequently developed to reduce the potential of motorcycle crashes. The new findings of this research can be used to:

    i) identify sites with the most potential for motorcycle crash risk reduction;
    ii) identify risk factors contributing to motorcycle crash risk and associated potential countermeasures to address these issues;
    iii) evaluate the crash risk reduction benefits of implemented countermeasures;
    iv) calculate the effect of various design alternatives on motorcycle crash risk.

9. The findings of this research are preliminary but will benefit researchers and practitioners, engineers and decision makers working in the area of motorcyclist safety not only in Vietnam but also in other countries that face similar issues. Therefore, to elaborate plans to improve motorcyclist safety, engineers or decision makers may use the developed crash risk models to identify hazardous sites and then using CoMFs measure to select appropriate countermeasures and also evaluate the effectiveness of countermeasures.

10. At policy level the impacts of this research are significant and, subject to its implementation, may be seen as:

i) significant improvement of motorcyclists safety;

ii) reduction in social and economic costs through the reduction of fatalities and serious injuries;

iii) better management of the road infrastructure;

iv) introduction of new legislation and enforcement practices;

v) development of enhanced behavioural patterns by motorcyclists;

vi) improvement of traffic conditions in cities in Vietnam and other similar countries.

12.2. Future Work

The developed models in this study presented limitations associated with the data collection process and the variables included in the models. Therefore it is felt that future research may address the following aspects:

1. The effect of the frequency and distances between major road intersections on the manoeuvre behaviour of motorcyclists and their contributions to crash risk.

2. The effect of roadside activities (e.g. shopping centres, the presence of schools and office buildings, land uses) and parking lots on the manoeuvre behaviour of motorcyclists and their influence on crash potentials.

3. The effect of lighting, visibility and weather conditions on the manoeuvre behaviour of motorcyclists and the contribution of these factors to the crash frequency and severity.

4. The effect of motorcyclists' characteristics such as ages, gender, knowledge and driving experience on their behaviour and on crash frequency and severity.

5. The use of a wider and possibly more representative data set collected from various cities and countries with similar traffic characteristics to those considered in this study to calibrate the developed models.

6. The applications of the Intelligent Traffic Systems (ITS) to improve the motorcyclists safety in urban environments in the conditions of low-income and middle-income countries.

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APPENDICES

Appendix A: An example of Conflict Modification Factor (CoMF) calculation process

Appendix B: An example of the existing HSM methodology calculation process

Appendix C: An example of the existing iRAP methodology calculation process

Appendix D: An example of the enhanced iRAP methodology calculation process

Appendix E: Dataset from Nguyen Tri Phuong Street for model field validation purpose

Appendix F: Dataset for model validation test purpose (compared with historical crash data and with existing methodologies from literature review)

Appendix G: Dataset from Nguyen Van Linh Street for model fitting

Appendix H: Paper 1 and Paper 2

APPENDIX A
AN EXAMPLE OF THE CoMF CALCULATION PROCESS

This appendix presents an example of calculating a value of CoMF as presented in Table 9.1 through to Table 9.9. As stated in section 9.1.2, CoMFs represent the relative change in the conflict frequency and they are defined by the ratio of the likelihood of a particular traffic condition to the likelihood of the baseline traffic condition.

For example, to determine CoMFs for the road surface condition factor, the calculation process is conducted in the following three steps (A, B and C).

Step A: Using the developed models to calculate the probability of rear-end and sideswipe conflicts for dry and wet surface conditions. The results are shown in Table A1.

Table A1. Probability of rear-end and sideswipe conflicts

Road surface condition	dry	wet
Probability of rear-end conflict	0.100	0.112
Probability of sideswipe conflict	0.175	0.261

Step B: Using Equation (9.2) and the outputs in step A to calculate the likelihood of rear-end and sideswipe conflicts for these two road surface conditions. For example, the likelihood of rear-end conflict for dry surface condition is calculated using Equation (9.2) and the output in Table A1 as follows:

$$likelihhod\ of\ rear\ end\ conflict\ = \frac{0.1}{1 - 0.10} = 0.11$$

The likelihood of rear-end and sideswipe conflicts for these two road surface conditions are shown in Table A2.

Table A2. Likelihood of road surface condition factor

Road surface condition	dry	wet
Probability of rear-end conflict	0.11	0.13
Probability of sideswipe conflict	0.211	0.353

Step C: Using Equation (9.3) and the outputs in step B to calculate CoMFs for the road surface condition factor. The baseline traffic condition is defined in this study as the normal driving condition in which motorcyclists can move freely in a traffic stream at a low crash risk level. In this case, the baseline traffic condition is the dry road surface condition. For example, CoMF of rear-end crash type for dry surface condition is calculated using Equation (9.3) and outputs in Table A2 as follows:

$$CoMF = \frac{0.13}{0.11} = 1.13$$

Consequently, the relative risk values of the road surface condition factor are shown in Table A3. The results indicate that the relative risks of both rear-end and sideswipe crashes are higher in wet road surface condition than that of in dry road surface condition.

Table A3. Relative risk values of road surface condition factor (see Table 9.8)

Road surface condition	dry	wet
Probability of rear-end conflict	1.00	1.13
Probability of sideswipe conflict	1.00	1.67

APPENDIX B
AN EXAMPLE OF THE HSM METHODOLOGY CALCULATION PROCESS

This appendix gives an example of estimating the expected average crash frequency of an individual site using the predictive method presented in the Highway Safety Manual (HSM) (AASHTO, 2009) (see section 2.2.1). In this example, the calculation process of estimating the average yearly crash frequency for a road segment on Nguyen Van Linh Street is described. The calculation process is similar to other road segments. Consequently, the calculation results for ten road segments are shown in Table B3.

As presented in Equation (2.2), the predictive model for an individual roadway segment combines the Safety Performance Function (SPF), the Crash Modification Factors (CMFs), and a calibration factor (C). The SPF of urban roads determined for multiple-vehicle crashes is as follows:

$$N_{brmv} = \exp(a + b \times \ln(AADT) + ln(L))$$

(Equation B1)

where, AADT is the average annual daily traffic (vehicle/day) on road segment; L is the length of road segment; a and b are regression coefficients.

For example, with regard to the four-lane divided urban road segments, the values of the coefficients a and b used in Equation (B1) are shown in Table B1.

Table B1. SPF coefficients for four-lane divided urban road segments (AASHTO, 2009)

Crash severity types	a	b
Total crashes	-12.34	1.36
Fatal-and-injury crashes	-12.76	1.28
Property-damage-only crashes	-12.81	1.38

To estimate the expected average crash frequency for a four-lane divided urban road segment of Nguyen Van Linh Street, the following three steps (A, B and C) are conducted.

Step A: Equation B1 is first applied to determine N_{brmv} using the coefficients for total crashes in Table B1. $N'_{brmv(FI)}$ for fatal-and-injury crashes and $N'_{brmv(PDO)}$ for property-damage-only crashes are then determined with Equation B1 using the coefficients for fatal-and-injury and property-damage-only crashes, respectively, in Table B1. An example of calculating these parameters for Nguyen Van Linh Street is as follows (L = 2170 m = 1.35 mile, AADT = 59704 vehicles/day):

$$N_{brmv} = \exp(-12.34 + 1.36 \times ln(59704) + ln(1.35)) = 1.37$$

$$N'_{brmv(FI)} = \exp(-12.76 + 1.28 \times ln(59704) + ln(1.35)) = 0.83$$

$$N'_{brmv(FI)} = \exp(-12.81 + 1.38 \times ln(59704) + ln(1.35)) = 0.87$$

Step B: N_{brmv} is then divided into components by severity level, $N_{brmv(FI)}$ for fatal-and-injury crashes and $N_{brmv(PDO)}$ for property-damage-only crashes. The following adjustments are made to assure that $N_{brmv(FI)}$ and $N_{brmv(PDO)}$ sum to N_{brmv}:

$$N_{brmv(FI)} = N_{brmv(TOTAL)} \left(\frac{N'_{brmv(FI)}}{N'_{brmv(FI)} + N'_{brmv(POD)}} \right)$$

(Equation E.2)

$$N_{brmv(POD)} = N_{brmv(TOTAL)} - N_{brmv(FI)}$$

(Equation E.3)

For the example of Nguyen Van Linh Street, these parameters are defined as follows:

$$N_{brmv(FI)} = 1.37 \times \frac{0.83}{(0.83 + 0.87)} = 0.67$$

$$N_{brmv(POD)} = 1.37 - 0.67 = 0.6$$

Step C: To separate $N_{brmv(FI)}$ and $N_{brmv(PDO)}$ into components by crash type, the proportions in Table (B2) are used.

Table B2. Distribution of multiple-vehicle crashes for four-lane divided urban road segment by crash type (AASHTO, 2009)

Crash type	Fatal-and-injury crashes	Property-damage-only crashes
Rear-end crash	0.832	0.662
Sideswipe crash	0.09	0.259
Other	0.078	0.079
Total	1.00	1.00

For the example of Nguyen Van Linh Street, the expected average crash frequency of rear-end crashes is calculated as follows:

$$N_{rear-end(FI+POD)} = 0.832 \times 0.67 + 0.662 \times 0.6 = 1.02$$

Therefore, the expected average crash frequency of rear-end crashes for 1000 m road length on Nguyen van Linh Street (L = 2170m) is defined as follows:

$$N_{rear-end(FI+POD)} = \frac{1.02}{2170\ (m)} \times 1000m = \ 0.5$$

Consequently, the calculation results of ten road segment are shown in Table B3.

Table B3. Expected average crash frequency of rear-end and sideswipe crashes for ten road segments (see Table 8.7 in Chapter 8)

Road name	N.V Linh	Bach Dang	2 Thang 9	N.T.P	D.B.Phu	N.H Tho	C.M.T-8	N.T.Thanh	Truong Chinh	T.D.Thang
Length (m)	2170	2542	3377	1295	2700	4680	1000	2000	1000	1000
AADT	59704	41621	49706	61402	78945	32706	43857	28865	65551	67563
Number of lanes	2.00	4.00	3.00	2.00	4.00	3.00	3.00	3.00	3.00	3.00
Lane width	4.00	3.75	3.50	3.75	3.50	3.50	3.50	3.50	3.50	3.50
Grade	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Road surface	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry
Total crash/year	**1.37**	**1.12**	**1.78**	**0.84**	**2.26**	**1.62**	**0.46**	**0.61**	**0.69**	**0.72**
N(F and I)'	0.83	0.68	1.08	0.51	1.37	0.98	0.28	0.37	0.42	0.43
N(POD)'	0.87	0.71	1.13	0.54	1.44	1.03	0.30	0.39	0.44	0.46
N (F and I)	0.67	0.55	0.87	0.41	1.10	0.79	0.23	0.30	0.34	0.35
Rear-end	0.56	0.45	0.72	0.34	0.92	0.66	0.19	0.25	0.28	0.29
Sideswipe	0.06	0.05	0.08	0.04	0.10	0.07	0.02	0.03	0.03	0.03
Other	*0.05*	*0.04*	*0.07*	*0.03*	*0.09*	*0.06*	*0.02*	*0.02*	*0.03*	*0.03*
N (POD)	0.70	0.57	0.91	0.43	1.16	0.83	0.24	0.31	0.36	0.37
Rear-end	0.47	0.38	0.60	0.29	0.77	0.55	0.16	0.21	0.24	0.24

Sideswipe	0.18	0.15	0.24	0.11	0.30	0.22	0.06	0.08	0.09	0.09
Other	*0.06*	*0.05*	*0.07*	*0.03*	*0.09*	*0.07*	*0.02*	*0.02*	*0.03*	*0.03*
Total (F+I+POD) for total road length										
Rear-end	1.02	0.83	1.32	0.63	1.68	1.21	0.35	0.46	0.52	0.53
Sideswipe	0.24	0.20	0.31	0.15	0.40	0.29	0.08	0.11	0.12	0.13
Other	0.11	0.09	0.14	0.07	0.18	0.13	0.04	0.05	0.05	0.06
Total (F+I+POD) for 1000 m road length										
Rear-end	0.47	0.33	0.39	0.48	0.62	0.26	0.35	0.23	0.52	0.53
Sideswipe	0.11	0.08	0.09	0.11	0.15	0.06	0.08	0.05	0.12	0.13
TT	0.58	0.41	0.48	0.60	0.77	0.32	0.43	0.28	0.64	0.66

APPENDIX C

THE EXISTING iRAP SRS FOR MOTORCYCLISTS

This appendix presents an example of calculating the Star Rating Score (SRS) for motorcyclists using the existing iRAP star rating system (see Section 10.4). In this example, the calculation process of motorcyclist SRS for a road segment on Nguyen Van Linh Street is described. The calculation process is similar to other road segments. As a result, the Star Rating Scores for motorcyclists for ten road segments are shown in Table C.

Road name: Nguyen Van Linh

Motorcyclist Star rating Scores

Run-off road (driver side)

Type of risk factor	**Category**	**Risk factor**	**Scores**
Road attribute (likelihood)			
Lane Width	Wide (>= 3.25m)	1	
Curvature	Straight	*1*	
Quality of Curve	Not applicable	*1*	
Delineation	Adequate	*1*	
Shoulder rumble strips	Not present	*1.25*	
Road condition	Good	*1*	
Grade	0 to <4%	*1*	
Skid resistance/grip	Sealed - adequate	*1*	
Product of road attribute (likelihood) risk factors			**1.25**
Road attribute (severity)			
Roadside severity - distance	>=10m	*0.1*	
Roadside severity – objects	Tree >10cm	*60*	
Paved shoulder width	**None**	*1*	
Product of road attribute (severity) risk factors			**6**
External flow influence	59704		0.5
Median traversibility	Non-Traversable		0
Operating speed	40		0.019
Run-off road (driver side) Star Rating Scores			**0**

Run-off road (passenger side)

Type of risk factor	Category	Risk factor	Scores
Road attribute (likelihood)			
Lane Width	Wide (>= 3.25m)	1	
Curvature	Straight	*1*	
Quality of Curve	Not applicable	*1*	
Delineation	Adequate	*1*	
Shoulder rumble strips	Not present	*1.25*	
Road condition	Good	*1*	
Grade	0 to <4%	*1*	
Skid resistance/grip	Sealed - adequate	*1*	
Product of road attribute (likelihood) risk factors			**1.25**
Road attribute (severity)			
Roadside severity - distance	1 to <5m	*0.8*	
Roadside severity – objects	Tree >10cm	*60*	
Paved shoulder width	**N/A**	*1*	
Product of road attribute (severity) risk factors			**48**
External flow influence	59704		**0.5**
Operating speed	40		**0.019**
Run-off road (passenger side) Star Rating Scores			**0.54**

Head-on (loss-of-control)

Type of risk factor	Category	Risk factor	Scores
Road attribute (likelihood)			
Lane Width	Wide (>= 3.25m)	1	
Curvature	Straight	*1*	
Quality of Curve	Not applicable	*1*	
Delineation	Adequate	*1*	
Centreline rumble strips	Not present	*1.25*	
Road condition	Good	*1*	
Grade	0 to <4%	*1*	
Skid resistance/grip	Sealed - adequate	*1*	
Product of road attribute (likelihood) risk factors			**1.25**
Road attribute (severity)			
Median type	Safety barrier - concrete	0	
Product of road attribute (severity) risk factors			**0**
External flow influence	41621		**0.5**
Median traversibility	Non-Traversable		**0**
Operating speed	40		**0**
Head-on (loss-of-control) Star Rating Scores			**0**

Head-on (overtaking)

Type of risk factor	Category	Risk factor	Scores
Road attribute (likelihood)			
Grade	0 to <4%	*1*	
Skid resistance/grip	Sealed - adequate	*1*	
Differential speed	Present	1.2	
Number of lanes	Two	0.02	
Product of road attribute (likelihood) risk factors			**0.024**
Road attribute (severity)			
Median type	Safety barrier - concrete	0	
Product of road attribute (severity) risk factors			**0**
External flow influence	59704		**0**
Operating speed	40		**0.019**
Head-on (overtaking) Star Rating Scores			**0**

Property Access

Type of risk factor	Category	Risk factor	Scores
Road attribute (likelihood)			
Property access points	Commercial access 1+	2	
Service road	Not present	1.5	
Product of road attribute (likelihood) risk factors			**3**
Road attribute (severity)			
Property access points	Commercial access 1+	50	
Product of road attribute (severity) risk factors			**50**
External flow influence	default		**0.01**
Operating speed	40		**0.019**
Property Access Star Rating Score			**0.0285**

Along

Type of risk factor	Category	Risk factor	Scores
Road attribute (likelihood)			
Motorcycle facilities	None	2	
Product of road attribute (likelihood) risk factors			**2**
Road attribute (severity)			
Motorcycle facilities	None	50	
Product of road attribute (severity) risk factors			**50**
External flow influence	59704		**0.1**
Operating speed	40		**0.019**
Along Star Rating Score			**0.19**

Motorcyclist Star Rating Score and Star Rating

Crash types	Star Rating Score	Star Rating
Run-off road (driver side)	0	
Run-off road (passenger side)	0.54	
Head-on (loss-of-control)	0	
Head-on (overtaking)	0	
Intersection	0	
Property access	0.029	
Along	0.19	
Total Score/Star Rating	**0.759**	5

Table C. Star Rating Score of motorcyclists for ten road segments

Road name	N.V Linh	Bach Dang	2 Thang 9	N.T.P	D.B.Phu	N.H Tho	C.M.T-8	N.T.Thanh	Truong Chinh	T.D.Thang
Star Rating	5	5	5	5	5	5	5	5	5	5
Total Risk (Star Rating Score)	**0.759**	**0.759**	**0.759**	**0.759**	**0.759**	**0.759**	**0.759**	**0.759**	**0.759**	**0.759**
Run-off	*0.54*	*0.54*	*0.54*	*0.54*	*0.54*	*0.54*	*0.54*	*0.54*	*0.54*	*0.54*
Head-on	*0.00*	*0.00*	*0.00*	*0.00*	*0*	*0*	*0*	*0*	*0*	*0*
Property access	*0.03*	*0.03*	*0.03*	*0.03*	*0.03*	*0.03*	*0.03*	*0.03*	*0.03*	*0.03*
Along	*0.19*	*0.19*	*0.19*	*0.19*	*0.19*	*0.19*	*0.19*	*0.19*	*0.19*	*0.19*
Fatality Estimate (crashes/road year)	**0.359**	**0.293**	**0.465**	**0.220**	**0.590**	**0.424**	**0.121**	**0.160**	**0.181**	**0.187**
Fatality Estimate (crashes/100m/year)	**0.017**	**0.012**	**0.014**	**0.017**	**0.022**	**0.009**	**0.012**	**0.008**	**0.018**	**0.019**
Run-off	*0.012*	*0.008*	*0.010*	*0.012*	*0.016*	*0.006*	*0.009*	*0.006*	*0.013*	*0.013*
Head-on	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*
Property access	*0.001*	*0.000*	*0.001*	*0.001*	*0.001*	*0.000*	*0.000*	*0.000*	*0.001*	*0.001*
Along	*0.0041*	*0.0029*	*0.0034*	*0.0043*	*0.0055*	*0.0023*	*0.0030*	*0.0020*	*0.0045*	*0.0047*

APPENDIX D

THE ENHANCED iRAP SRS FOR MOTORCYCLISTS

This appendix presents an example of calculating the Star Rating Score (SRS) for motorcyclists using the enhanced iRAP star rating system (see section 10.5). In this example, the calculation process of motorcyclist SRS for a road segment on Nguyen Van Linh Street is described. The calculation process is similar to other road segments. As a result, the Star Rating Scores of motorcyclists for five road segments are shown in Table D.

Road name: Nguyen Van Linh

Motorcyclist Star rating Scores

Rear-end risk score

Type of risk factor	**Category**	**Risk factor**	**Scores**
Road attribute (likelihood)			
Speed	40.0 km/h	*0.98*	
Speed difference	5.0 km/h	*1*	
Traffic density	77 vehicles/1000m2	*1.05*	
Lateral clearance	2.6 m	*1.45*	
Front distance	2.9 m	*1.1*	
Longitudinal gap	2.7 m	*0.98*	
Road surface condition	Dry	*1*	
Presence of segregated motorcycle lane	Absence	*1*	
Product of road attribute (likelihood) risk factors			**1.6**
Road attribute (severity)			
Segregated motorcycle lane	Absence	*50*	
Product of road attribute (severity) risk factors			**50**
External flow influence	59704		**0.1**
Operating speed	40		**0.019**
Rear-end Star Rating Scores			**0.16**

Sideswipe risk score

Type of risk factor	Category	Risk factor	Scores
Road attribute (likelihood)			
Speed	40.0 km/h	*0.9*	
Speed difference	5.0 km/h	*4.1*	
Traffic density	77 vehicles/1000m2	*1.05*	
Lateral clearance	2.6 m	*0.78*	
Front distance	2.9 m	*1.76*	
Longitudinal gap	2.7 m	*0.69*	
Lateral gap	1.5 m	*1*	
Road surface condition	Dry	*1*	
Presence of segregated motorcycle lane	Absence	*1*	
Product of road attribute (likelihood) risk factors			**3.67**
Road attribute (severity)			
Segregated motorcycle lane	Absence	*50*	
Product of road attribute (severity) risk factors			**50**
External flow influence	59704		**0.1**
Operating speed	40		**0.019**
Sideswipe Star Rating Scores			**0.36**

Risk scores of motorcyclists using the enhanced iRAP SRS methodology

Crash types	Star Rating Score	Star Rating
Run-off road (driver side)	0	
Run-off road (passenger side)	0.54	
Head-on (loss-of-control)	0	
Head-on (overtaking)	0	
Property access	0.029	
Along	0.19	
Rear-end	***0.16***	
Sideswipe	***0.36***	
Total Score/Star Rating	**1.28**	5

Table D. Risk scores of motorcyclists using enhanced iRAP model (see Table 10.8)

Crash types	N.V Linh	Bach Dang	2 Thang 9	N.T.P	D.B.Phu
Run-off road (driver side)	0	0	0	0	0
Run-off road (passenger side)	0.54	0.54	0.54	0.54	0.54
Head-on (loss-of-control)	0	0	0	0	0
Head-on (overtaking)	0	0	0	0	0
Property access	0.029	0.029	0.029	0.029	0.029
Along	0.19	0.19	0.19	0.19	0.19
Rear-end	***0.16***	***0.11***	***0.13***	***0.19***	***0.26***
Sideswipe	***0.36***	***0.23***	***0.30***	***0.42***	***0.45***
Total Score/Star Rating	**1.28**	**1.09**	**1.20**	**1.37**	**1.47**

APPENDIX E

DATASET FROM NGUYEN TRI PHUONG STREET

This dataset was used for the purpose of model field validation (see section 8.2)

Table E. Statistics of dataset from Nguyen Tri Phuong Street

Time periods	Traffic volume (motorcycles /hour)	Average density (motorcycles /1000m^2)	Average speed (m/s)	Observed rear-end conflicts	Observed sideswipe conflict	Average Front distance (m)	Average Lateral clearance (m)	Average Longitudinal gap (m)	Average Lateral gap (m)
6:00am-7:00am	3137	74	9.75	9	5	3.0	2.7	2.5	1.5
7:00am-8:00am	4297	102	8.72	27	10	2.4	1.8	1.9	1.4
8:00am-9:00am	3471	82	9.45	24	14	2.8	2.4	2.3	1.5
3:00pm-4:00pm	2971	70	9.91	5	2	3.1	2.8	2.6	1.5
4:00pm-5:00pm	3975	90	9.15	22	12	2.6	2.2	2.1	1.4
5:00pm-6:00pm	5284	125	7.95	46	15	2.1	1.2	1.6	1.4

APPENDIX F
DATASET FROM TEN ROAD SEGMENTS

This dataset was used for the purpose of model validation test (see section 8.3)

Table F1. Geometry characteristics of ten road segments

Location	Road name	Road length (m)	Number of lanes	Lane width (m)
1	Nguyen Van Linh	2170	2	4
2	Bach Dang	2542	4	3.75
3	Duong 2-9	3377	3	3.5
4	Nguyen Tri Phuong	1295	2	3.5
5	Dien Bien Phu	2700	4	3.5
6	Nguyen Huu Tho	4680	3	3.5
7	Cach Mang T-8	1000	3	3.5
8	Nguyen Tat Thanh	2000	3	3.5
9	Truong Chinh	1000	3	3.5
10	Ton Duc Thang	1000	3	3.5

Table F2. Traffic characteristics of ten road segments and historical crash data

Location	Volume (vehicles/day)	Density (vehicles/1000m^2)	Average speed (m/s)	Crash records (2008-2015)	
				Rear-end	Sideswipe
1	59704	89	9.68	21	5
2	41621	68	9.99	9	2
3	49706	72	9.83	16	4
4	61402	94	9.48	27	7
5	78945	76	9.19	35	9
6	32706	72	9.83	11	3
7	43857	75	9.71	12	4
8	28865	68	9.99	11	2
9	65551	83	9.41	27	15
10	67563	85	9.33	24	14

- Historical crash data collection source: Danang Department of Transport

APPENDIX G

DATASET FROM NGUYEN VAN LINH STREET

This dataset was used for model fitting and assessing the goodness-of-fit of model (see Chapter 6)

Table G. Data set used for the logistic regression analysis

ID	choice	Lo_n^{n-1}	Lo_n^m	V_n^{n-1}	V_n^m	La_{n-1}	Te_{n-1}	Te_m
1	0	5.3	3.18	2.78	1.95	1.01	M	C
2	0	4.1	2.26	2.29	1.84	1.02	M	C
3	1	2.6	1.2	3.03	2.18	3.99	M	C
4	1	1	1.2	3.47	2.63	4.04	M	C
5	1	1.2	1.5	4.11	2.76	4.15	M	C
6	0	4.4	2.04	-0.59	-1.69	1.55	M	C
7	0	4.8	3.29	-0.65	-2.49	1.69	M	C
8	0	5.2	4.59	-0.78	-2.6	1.58	M	C
9	0	5.6	6.1	-0.85	-3.02	1.28	M	C
10	0	5.6	7.2	-1.03	-2.97	1.08	M	C
11	0	1.8	2.27	0.89	1.68	2.1	M	M
12	0	1.4	3.7	0.77	1.64	2.04	M	M
13	1	1	5.34	1.52	3.3	1.81	M	M
14	1	1.1	6.66	1.01	2.68	1.39	M	M
15	1	1.3	7.2	0.92	2.28	1.35	M	M
16	0	3.4	1.38	1.47	0.73	2.08	M	M
17	0	3.1	1.38	0.52	-0.66	1.92	M	M
18	0	3	1.2	0.29	-1.25	1.74	M	M
19	0	2.8	2.03	0.37	-8.52	0.83	M	M
20	0	2.9	1.2	-0.17	-1.69	1.12	M	M
21	0	2.9	1.2	-0.02	-1.48	1.33	M	M
22	0	1.8	1.73	0.91	-1.94	0.72	M	M
23	1	1.1	1.2	1.37	1.79	1.09	M	M
24	1	1	1.2	0.9	-0.25	1.65	M	M
25	1	1.1	1.2	1.25	0.87	2.44	M	M
26	1	1	1.38	1.35	0.77	2.62	M	M
27	1	1.3	1.83	1.51	0.9	2.87	M	M
28	0	3.4	1.33	1.27	1.21	1.95	M	C
29	0	2.7	1.35	1.37	1.96	2.06	M	C
30	0	2	1.2	1.55	1.17	2.15	M	C

31	1	1.3	1.7	1.4	2.04	3.88	M	M
32	0	2.4	2.15	0.66	1.53	3.62	M	M
33	0	2.4	1.34	-0.14	1.06	3.5	M	M
34	0	2.6	1.2	-0.41	1.01	0.94	M	M
35	0	2.5	1.24	0.2	1.21	1.01	M	M
36	0	2.5	1.2	0.14	1.08	0.71	M	M
37	0	2.5	2.85	2.41	1.98	0.88	M	C
38	1	1.3	2.05	2.3	1.61	4.22	M	C
39	1	1.1	1.2	2.86	2.16	4.29	M	C
40	1	1.7	1.2	3.25	2.03	4.27	M	C
41	1	3.6	1.35	3.83	2.61	4.18	M	C
42	0	2.6	4.51	2.49	0.71	0.81	M	M
43	1	1.8	5.28	1.59	1.6	1.18	M	M
44	1	1.2	5.78	1.39	1.18	1.25	M	M
45	1	1.1	6.89	2.13	2.21	1.11	M	M
46	1	1	7.2	1.68	1.61	0.9	M	M
47	1	1.3	7.2	1.35	1.62	0.81	M	M
48	0	1.2	1.2	-0.2	-1.47	0.96	M	M
49	0	1.3	1.49	-0.06	-0.65	1.16	M	M
50	0	1.1	1.39	0.25	-0.38	0.81	M	M
51	0	1.1	1.2	0.1	-0.8	0.75	M	M
52	0	3.4	3.91	0.44	0.24	3.88	M	C
53	0	3.2	3.75	0.25	0.32	3.88	M	C
54	0	3	3.61	0.53	0.28	3.88	M	C
55	0	2.6	3.37	0.68	0.48	3.88	M	C
56	0	2.7	3.52	-0.18	-0.32	3.88	M	C
57	0	3.8	2.37	-0.75	-0.41	3.88	M	C
58	0	3.9	1.89	-0.06	-0.66	3.88	M	C
59	0	4.2	1.64	-0.66	-0.71	3.88	M	C
60	1	2.3	2.73	3.49	1.68	3.75	M	M
61	1	1.3	4.11	4.04	2.79	4.04	M	M
62	1	1.7	5.14	3.96	2.08	4.07	M	M
63	0	4.4	1.93	-0.58	0.24	0.71	M	M
64	0	4.4	2.57	-0.1	0.22	0.71	M	M
65	0	2.7	1.2	0.8	-2.45	2.86	M	C
66	0	2.2	1.2	1.04	0.54	3.06	M	C
67	1	1.9	1.2	0.52	0.96	3.1	M	M
68	1	1.6	1.2	0.7	1.1	2.8	M	M
69	1	1.3	1.5	0.59	1	2.24	M	M
70	1	1	2.14	0.62	1.33	1.77	M	M
71	0	3.1	1.21	1.47	0.66	3.77	M	C
72	1	2.4	1.2	1.42	1.12	3.89	M	M
73	1	1.6	1.2	1.56	1.06	4.05	M	M

74	1	1	1.2	1.49	0.6	4.05	M	M
75	1	1.2	1.3	1.37	0.31	4.16	M	M
76	1	1	1.44	1.75	0.3	4.27	M	M
77	1	1.4	1.2	1.56	0.63	4.23	M	M
78	0	3	2.45	-1.09	-0.64	3.88	M	M
79	0	3.4	1.98	-0.76	-1.31	3.88	M	M
80	0	3.3	2.5	0.24	-1.05	3.88	M	M
81	0	3.3	3.61	-0.09	-2.21	4.48	M	M
82	0	1.1	1.2	0.27	0.32	0.77	M	C
83	1	1	1.2	0.34	0.06	2.37	M	M
84	1	1	1.2	0.21	-0.17	2.18	M	M
85	0	3.7	1.55	2.85	2.85	2.78	M	C
86	0	2.3	2.84	2.94	2.64	2.41	M	C
87	1	1	4.26	3.04	2.93	2.56	M	M
88	1	1	5.72	3.28	2.94	2.9	M	M
89	0	1.3	1.32	0.88	-0.93	0.71	M	M
90	0	1.1	1.2	0.28	0.33	0.87	M	M
91	1	1	1.2	0.95	1.98	2.84	M	M
92	1	1.3	1.35	1.87	0.87	2.96	M	M
93	1	1.3	1.24	2.09	1.88	3.18	M	M
94	1	1.7	5.11	1.05	7.56	3.88	M	C
95	1	1	7.2	1.61	8.25	4.4	M	C
96	1	1.2	7.2	2.39	9.29	4.33	M	C
97	1	1.3	7.2	2.21	9.34	4.39	M	C
98	1	2.4	7.2	2.33	9.03	3.88	M	C
99	1	1.9	1.4	1.27	2.15	2.51	M	M
100	1	1.1	2.28	1.69	1.79	2.58	M	M
101	1	1.4	3.24	1.36	1.92	2.32	M	M
102	1	1	4.74	2.09	3.02	2.22	M	M
103	0	1.1	1.49	0.7	-0.04	0.71	M	M
104	1	1	2.1	0.71	0.95	3.06	M	M
105	1	1.3	2.49	1	0.8	3.18	M	M
106	1	1.4	2.81	1.45	0.63	3.32	M	M
107	1	1.4	4.01	1.91	2.37	3.24	M	M
108	0	3.7	7.2	2.04	8.92	2.06	M	C
109	0	3	7.2	1.42	8.55	2.03	M	C
110	0	2.1	7.2	1.84	8.12	2.19	M	C
111	1	1	7.2	2.26	9.05	2.12	M	C
112	1	1	7.2	1.89	9.12	2.17	M	C
113	1	1	7.2	1.63	8.72	2.03	M	C
114	0	1.5	1.59	1.09	0.79	3.28	M	C
115	1	1	1.2	1.75	0.94	4.03	M	M
116	1	1.2	1.48	1.7	1.29	3.95	M	M

117	1	1.3	1.33	2.16	1.64	4.13	M	M
118	1	2.7	1.38	2.78	2.1	4.15	M	M
119	1	1.4	1.2	1.92	3.05	3.38	M	C
120	1	1.1	2.55	2.94	3.55	3.65	M	C
121	1	2.9	4.35	3.61	3.62	3.7	M	C
122	0	4.3	7.2	3.71	-3.09	0.71	M	C
123	0	2.8	7.2	2.95	6.75	0.71	M	C
124	1	1.2	7.2	3.24	9.84	3.42	M	C
125	1	1	7.2	3.9	10.36	3.25	M	C
126	0	3.6	2.34	2.31	2.28	0.71	M	C
127	1	2.3	3.57	2.48	2.49	3.71	M	M
128	1	1	4.97	2.93	2.78	3.74	M	M
129	1	1	7.2	3.49	4.2	3.84	M	C
130	1	2.8	7.2	3.86	1.89	4	M	C
131	0	4.6	1.2	1.16	3.28	1.97	M	C
132	0	4.2	1.2	0.83	3.15	1.88	M	C
133	0	3.6	2.31	1.18	3.08	1.63	M	C
134	0	4.7	1.25	0.57	-0.75	3.75	M	C
135	0	4.1	1.2	1.03	1.06	3.91	M	C
136	0	3.5	1.2	1.33	-1.76	4	M	C
137	1	2.9	2.15	1.26	2.43	3.88	M	M
138	1	2.2	3.32	1.44	2.39	3.88	M	M
139	1	1.6	1.2	0.88	1.96	3.38	M	M
140	1	1	1.2	1.96	1.61	3.39	M	M
141	1	1.2	1.72	1.74	2.23	3.25	M	M
142	0	1.2	1.2	0.76	1.48	1.98	M	M
143	1	1	1.49	1.04	1.72	1.98	M	M
144	1	1.1	2.42	1.17	1.87	2.12	M	M
145	1	1.4	3.14	0.99	1.44	2.3	M	M
146	1	1	3.89	1.17	1.51	2.23	M	M
147	0	3.6	1.2	0.14	0.51	0.95	M	C
148	0	3.7	1.2	-0.16	-0.67	0.72	M	C
149	1	3.7	1.49	0.11	1.78	3.88	M	M
150	1	3.6	2.58	0.32	2.28	3.88	M	M
151	1	3.2	3.94	0.76	2.75	3.88	M	M
152	0	4.3	1.38	3.26	2.72	1.64	M	C
153	1	2.5	1.27	3.56	3.32	4.25	M	C
154	1	1	3.01	3.55	3.5	4.23	M	C
155	1	1.1	4.95	3.81	3.89	4.3	M	C
156	0	1.8	1.66	1.63	3.14	3.88	M	C
157	0	1.5	1.2	0.59	1.92	3.88	M	C
158	1	1	1.2	1.84	3.26	3.88	M	C
159	1	1.2	2.63	1.68	3.41	3.88	M	C

160	0	1	1.2	-0.23	0.85	1.43	M	M
161	1	1	3.19	0.3	1.16	3.69	M	M
162	1	1	3.77	0.4	1.16	3.66	M	M
163	1	1.2	4.35	0.5	1.14	3.71	M	M
164	1	3.5	1.74	0.77	0.66	3.88	M	M
165	1	2.9	2.29	1.26	1.09	3.88	M	M
166	1	2.4	2.78	0.99	0.98	3.88	M	M
167	1	2	3.34	0.85	1.13	3.88	M	M
168	1	1.3	4.04	1.27	1.39	3.88	M	M
169	0	4.7	4.25	0.49	-3.57	1.41	C	M
170	0	4.8	6.47	-0.19	-4.49	1.17	C	M
171	0	4.9	7.2	-0.19	-5.04	0.88	C	M
172	0	4.9	7.2	-0.19	-5.97	0.71	C	M
173	1	1.5	1.2	3.37	1.79	3.88	M	C
174	1	1.2	1.54	2.54	1.4	3.88	M	C
175	1	1.2	2.36	2.94	1.65	3.88	M	C
176	1	2.4	3.04	2.4	1.37	3.88	M	C
177	1	3.3	3.2	1.75	0.33	3.88	M	C
178	0	2.7	3.39	-0.43	-2.5	0.77	M	C
179	0	3	4.13	-0.6	1.5	1.13	M	C
180	0	3.3	4.63	-0.57	-3.32	1.08	M	C
181	0	3.5	5.25	-0.46	0.72	0.85	M	C
182	0	4.1	1.2	-0.02	0.77	1.43	M	M
183	0	4.4	1.47	-0.61	0.65	1.23	M	M
184	0	4.7	1.42	-0.59	0.65	1.24	M	M
185	0	3.2	4.4	0.53	0.14	1.56	M	M
186	0	3.3	4.94	-0.32	-0.54	1.76	M	M
187	0	3.4	5.37	-0.14	0.86	1.99	M	M
188	0	3.3	4.91	0.19	-0.92	2.04	M	M
189	0	3.3	4.77	-0.01	-0.28	2.03	M	M
190	1	1	1.34	1.62	2.12	3.61	M	C
191	1	1	1.4	1.63	2.18	3.37	M	C
192	1	1	2.55	1.99	2.32	3.5	M	C
193	1	2.4	4	2.7	2.91	3.4	M	C
194	1	3.6	5.48	2.55	2.96	3.53	M	C
195	1	1.6	1.48	1.44	1.22	1.87	M	M
196	1	1.4	1.2	0.38	0.97	1.88	M	M
197	1	1.1	1.2	0.72	1.07	1.9	M	M
198	1	1	1.2	0.73	1.16	1.93	M	M
199	1	1.2	1.74	-0.91	1.33	1.82	M	M
200	1	1	2.18	0.67	0.89	1.79	M	M
201	1	1	2.55	0.37	0.73	1.77	M	M
202	0	3.2	4.55	0.6	8.23	3.88	M	C

203	1	2.6	4.75	1.29	7.93	3.88	M	M
204	1	2.1	4.55	0.91	-0.42	3.88	M	M
205	1	1.3	4.8	1.52	0.52	3.88	M	M
206	1	1.4	5.24	1.88	0.88	3.88	M	M
207	1	1.4	5.41	1.53	0.34	3.88	M	M
208	1	1.2	5.75	1.69	0.67	3.88	M	M
209	0	1	2.19	0.96	0.61	1.77	M	M
210	1	1	2.28	0.95	0.21	1.78	M	M
211	1	1.2	2.55	0.81	0.52	1.67	M	M
212	1	1.4	2.54	1.08	0	1.67	M	M
213	1	1	2.4	1.13	-0.28	1.84	M	M
214	0	1.9	1.83	-0.24	0.34	0.95	M	M
215	1	1.9	2.81	0.14	1.76	3.88	M	M
216	1	2	4.39	-0.13	3.21	3.88	M	M
217	1	1.9	6.09	0.24	3.46	3.88	M	M
218	1	1.5	7.2	0.74	4.1	3.88	M	M
219	0	2.1	1.2	0.86	-0.41	0.94	M	M
220	0	1.8	1.2	0.52	-0.71	0.71	M	M
221	1	1.4	1.33	0.74	0.38	3.88	M	M
222	1	1	1.83	1.18	1.02	3.88	M	M
223	1	1.1	2.61	1.42	1.56	3.88	M	M
224	1	1.4	3.46	1.08	1.7	3.88	M	M
225	0	1.2	1.92	0.07	-1.75	0.75	M	M
226	0	1.2	2.91	-0.05	-1.98	0.71	M	M
227	0	1.2	4.04	-0.11	-2.27	0.71	M	M
228	0	1.5	6.17	1.48	0.33	1.12	M	C
229	1	1	6.23	1.53	-0.28	3.95	M	C
230	1	1.1	6.59	1.42	0.73	3.84	M	C
231	0	1.6	1.2	-0.17	0.4	0.83	M	M
232	0	1.4	1.2	0.54	0.8	0.83	M	M
233	0	1.2	1.95	0.25	0.61	0.9	M	M
234	1	1	2.94	0.81	1.95	3.88	M	M
235	1	1.2	3.98	1.31	2.09	3.88	M	M
236	0	1.2	1.2	1.13	-2.13	0.71	M	C
237	1	1	1.47	1.21	-0.71	1.43	M	M
238	1	1.4	1.2	1.88	0.62	1.79	M	M
239	1	1.5	1.37	2.16	1.18	2.26	M	M
240	1	2.6	1.6	2.21	0.46	2.66	M	M
241	0	2	2.62	0.58	-0.95	0.89	M	M
242	0	1.7	2.5	0.59	-0.72	0.87	M	M
243	1	1.2	2.37	0.97	-0.23	3.26	M	M
244	1	1	2.31	1.1	-0.04	3.25	M	M
245	1	1.2	2.62	1.7	0.65	3.15	M	M

246	0	1	1.2	0.28	0.35	0.87	M	C
247	1	1	2.37	0.64	0.06	4.34	M	C
248	1	1.2	2.29	0.77	-0.16	4.35	M	C
249	1	1.3	2.41	1	0.19	4.42	M	C
250	1	1	1.52	1.22	-1.77	4.46	M	C
251	1	1.6	3.14	1.47	3.25	3.88	M	C
252	0	3.7	7.2	0.01	-1.05	3.88	M	C
253	0	3.4	7.2	0.7	-0.93	3.88	M	C
254	0	3	2.67	0.72	-1.12	3.88	M	C
255	0	2.7	1.2	0.64	-1.57	3.88	M	C
256	0	3.6	1.49	0.75	1.29	3.71	M	C
257	0	2.9	1.2	1.57	1.35	3.57	M	C
258	1	1.6	2.42	2.49	2.84	3.49	M	C
259	1	1.2	3.78	2.84	2.78	3.87	M	C
260	1	1.1	5.2	2.66	2.87	3.88	M	C
261	0	2.9	4.48	2.08	-1.49	1.01	M	C
262	1	1.9	3.92	2.12	-1.07	1.16	M	M
263	1	1	3.2	2.39	-1.46	3.88	M	M
264	1	1.4	2.5	2.31	-1.4	3.88	M	M
265	1	1.7	1.49	2.49	-2.04	3.88	M	M
266	1	3.2	1.2	2.95	-1.97	3.88	M	M
267	0	1.2	1.2	1.15	0.07	0.79	M	M
268	1	1.4	1.33	1.66	2.15	3.88	M	M
269	1	1	2.26	2.37	3.86	3.88	M	M
270	1	1.9	4.22	2.24	3.92	3.88	M	M
271	0	1.9	1.2	-0.76	-1.16	1.23	M	M
272	0	2.3	1.2	-0.84	-1.13	1.68	M	M
273	0	2.7	1.65	-0.66	-1.13	1.99	M	M
274	0	3	7.2	0.13	-1.81	0.73	C	C
275	0	2.7	7.2	0.73	-2.24	0.71	C	C
276	0	2.6	7.2	0.09	-2.28	0.71	C	C
277	0	2.6	7.2	0.04	-2.68	0.97	C	C
278	0	2.4	7.2	0.38	-2.76	0.97	C	C
279	0	3.5	4.47	0.32	8.2	0.84	M	C
280	0	2.9	7.2	1.15	8.51	0.83	M	C
281	0	2.7	7.2	0.52	8.66	1	M	C
282	0	2.6	7.2	0.07	8.35	1	M	C
283	0	2.4	7.2	0.44	8.67	1.2	M	C
284	0	2.5	7.2	-0.2	8.23	1.14	M	C
285	1	1.3	1.71	0.56	1.1	3.88	M	C
286	1	1.4	3.05	1.79	2.7	3.88	M	C
287	1	1.3	4.37	1.43	2.66	3.88	M	C
288	1	1.6	5.91	2.59	3.07	3.88	M	C

289	0	2.4	1.34	-0.27	0.61	1.27	M	M
290	0	2.1	1.2	0.67	1.37	1.13	M	M
291	0	1.9	1.61	0.26	0.5	1.09	M	M
292	0	1.6	3.09	0.76	1.06	0.95	M	M
293	0	1.5	3.53	0.08	0.2	1	M	M
294	1	3.7	1.29	1.16	1.04	3.88	M	M
295	1	3	1.2	1.32	0.52	3.88	M	M
296	1	1.8	1.21	2.35	1.31	3.88	M	M
297	1	1	1.54	1.62	0.66	3.88	M	M
298	1	1.1	2.15	2.27	1.23	3.88	M	M
299	1	1.4	2.78	2.63	1.28	3.88	M	M
300	0	4.9	1.97	1.11	-0.39	1.07	M	M
301	0	4.1	1.36	1.68	-0.93	1.02	M	M
302	0	3.4	1.68	1.44	-0.63	0.82	M	M
303	1	2.3	1.2	2.25	2.42	4.01	M	M
304	1	1.1	1.45	2.33	1.6	3.92	M	M
305	0	2.9	7.2	0.08	7.05	4.31	M	C
306	0	3.2	7.2	-0.55	7.13	4.19	M	C
307	0	3.3	7.2	-0.24	7.55	4.19	M	C
308	0	3.4	7.2	-0.25	7.19	4.34	M	C
309	0	3.5	7.2	-0.2	7.46	4.45	M	C
310	0	1.3	1.37	0.8	-1.75	3.88	M	M
311	1	1.1	1.55	0.41	0.49	3.88	M	M
312	1	1	1.42	0.55	-0.04	4.29	M	M
313	1	1.3	1.94	1.32	1.09	4.03	M	M
314	1	1.4	2.48	1.55	1.08	3.95	M	M
315	1	1.2	2.89	1.61	0.83	3.82	M	M
316	1	2.2	3.42	1.89	1.07	3.9	M	M
317	0	1.8	1.22	0.38	-0.12	0.86	M	C
318	0	1.5	1.2	0.75	0.73	1.02	M	C
319	0	1.2	1.2	0.47	-0.17	0.85	M	C
320	1	1	1.2	0.62	0.32	3.88	M	M
321	1	1	1.2	0.65	0.44	3.88	M	M
322	1	1.2	1.46	0.89	0.22	3.88	M	M
323	1	1.2	1.25	0.69	0.41	3.88	M	M
324	0	1	1.71	0.65	0.23	3.88	M	C
325	1	1	1.2	0.81	0.37	3.88	M	M
326	1	1.1	1.5	1.55	1.78	4.17	M	M
327	1	1.4	2.25	0.69	1.56	3.85	M	M
328	1	1.1	3.38	1.35	2.29	3.62	M	M
329	0	2.6	6.28	1.94	9.31	1.11	M	C
330	1	2	7.2	1.31	8.72	3.96	M	C
331	1	1.5	7.2	1.02	8.72	4.03	M	C

332	1	1	7.2	1.08	8.19	3.94	M	C
333	1	1	7.2	0.77	7.95	3.79	M	C
334	1	1	7.2	0.18	7.57	3.72	M	C
335	0	1	3.04	-0.21	0.12	0.98	M	M
336	1	1	3.03	0.37	-0.02	4.14	M	M
337	1	1	3.7	0.55	1.37	4.08	M	M
338	1	1	4.4	0.92	1.42	4.19	M	M
339	1	1.4	4.92	0.97	1.05	4.26	M	M
340	0	1.6	1.58	1.05	-0.46	3.51	M	M
341	0	1	1.77	1.41	-0.43	3.44	M	M
342	1	1	1.6	0.6	-0.29	3.88	M	M
343	1	1.2	1.93	1.73	0.68	3.88	M	M
344	1	1	2.01	1.12	0.18	3.88	M	M
345	1	1	2.09	0.47	0.16	3.88	M	M
346	1	1.5	2.35	0.9	0.51	3.88	M	M
347	1	1.7	2.54	0.5	0.39	3.88	M	M
348	1	2	2.86	0.48	0.64	3.88	M	M
349	0	1.1	3.33	1.36	0.13	2.9	M	C
350	1	1	3.55	1.04	0.43	2.82	M	M
351	1	1.4	3.57	0.21	0.05	2.66	M	M
352	1	1.2	3.77	1.27	0.4	2.84	M	M
353	1	1	4.33	0.92	1.12	2.62	M	M
354	1	1	4.68	0.77	0.69	2.69	M	M
355	1	1.5	4.89	0.99	0.43	2.74	M	M
356	0	2.4	1.2	0.38	0.31	3.88	M	C
357	1	1.9	1.22	0.88	0.17	3.88	M	M
358	1	1.6	1.39	0.67	0.35	3.88	M	M
359	1	1.1	2.14	1.02	1.51	3.88	M	M
360	1	1	2.68	1.2	1.09	3.88	M	M
361	1	1.3	3.46	1.56	1.54	3.88	M	M
362	1	1.1	4.19	1.59	1.45	3.88	M	M
363	1	2	6.81	2.3	-0.31	3.4	M	C
364	1	1	6.94	2.18	0.3	3.55	M	C
365	1	1.3	7.2	2.63	8.45	3.6	M	C
366	1	2.2	7.2	3.69	9.46	3.62	M	C
367	1	4.2	7.2	4.04	9.93	3.75	M	C
368	0	3	1.32	0.81	-1.07	3.88	M	C
369	0	2.4	1.33	1.05	-0.75	3.88	M	C
370	0	1.9	1.34	1.04	-0.86	3.88	M	C
371	1	1.5	4.23	1.03	7.85	3.88	M	M
372	1	1	1.2	1.07	-6.09	3.88	M	M
373	1	1	1.51	0.75	0.74	3.88	M	M
374	1	1.1	2.07	1.4	1.12	3.88	M	M

375	0	2.7	6.73	1.03	2.94	1.63	M	C
376	0	2.2	7.2	1.05	2.99	1.67	M	C
377	0	1.6	7.2	1.19	10.19	1.71	M	C
378	0	1.2	7.2	0.69	9.09	1.77	M	C
379	1	1	7.2	0.47	9.59	1.74	M	C
380	1	1	7.2	0.1	8.81	1.64	M	C
381	0	3.2	4.17	2.77	-3.68	3.73	M	C
382	0	1.9	2.9	2.51	2.54	3.91	M	C
383	1	1	1.43	1.7	1.61	3.88	M	M
384	1	1.3	1.25	1.67	1.74	3.88	M	M
385	1	1	2.18	2.05	1.93	3.88	M	M
386	0	3.5	1.2	2.13	1.34	1.19	M	C
387	0	2.8	1.2	1.48	1.12	1.47	M	C
388	0	1.7	1.2	2.16	1.88	1.75	M	C
389	1	1	1.76	1.77	1.84	3.67	M	C
390	1	1.3	2.79	2.27	2.1	3.64	M	C
391	1	1.5	1.41	1.07	1.52	3.88	M	C
392	1	1	2.14	1.37	1.55	3.88	M	C
393	1	1.2	3.02	1.19	1.8	3.88	M	C
394	0	3.2	1.4	2.33	-1.51	0.9	M	M
395	1	2.3	2.86	1.92	1.73	3.88	M	M
396	1	1.5	3.62	1.68	1.61	3.88	M	M
397	1	1.4	4.28	2.12	1.37	3.88	M	M
398	1	1	5.21	2.1	1.91	3.88	M	M
399	0	3.1	1.36	3.04	2.16	1.13	M	C
400	0	2.1	1.27	2.13	2.01	1.36	M	C
401	1	1	1.2	3.06	2.48	3.74	M	C
402	1	1	2.21	2.2	2.51	3.71	M	C
403	1	1.2	4.74	2.51	4.78	2.48	M	C
404	1	1.2	7.2	2.12	10.09	2.56	M	C
405	1	1	7.2	2.06	10.68	2.59	M	C
406	1	1.8	7.2	1.97	9.5	2.75	M	C
407	1	2.6	7.2	1.64	10.08	2.72	M	C
408	0	3.2	6.86	2.52	10.7	0.97	M	C
409	1	1.5	7.2	3.41	11.63	3.64	M	C
410	1	1.2	7.2	3.51	11.68	3.76	M	C
411	1	2.5	7.2	4.47	13.28	3.96	M	C
412	1	4.5	7.2	3.98	11.45	4.08	M	C
413	0	4.2	1.2	0.28	0.72	3.94	M	C
414	0	4	1.33	0.29	1	4.08	M	C
415	1	3.8	1.2	0.63	1.25	3.88	M	C
416	1	3.4	1.46	0.69	1.12	3.88	M	C
417	1	3.2	2.19	0.61	1.54	3.88	M	C

418	1	2.9	2.98	0.61	1.63	3.88	M	C
419	0	1.4	3.39	0.95	-1.27	0.85	M	C
420	1	1	2.8	1.84	-1.16	4.38	M	M
421	1	1.2	2.39	1.53	-0.82	4.41	M	M
422	1	1.2	2.25	1.86	-0.28	4.44	M	M
423	1	1.5	1.93	0.69	-0.64	4.39	M	M
424	0	4	4.51	-0.42	-0.56	4.22	M	M
425	0	4	4.64	-0.14	-0.25	4.27	M	M
426	0	4.4	5.13	-0.65	-1	4.24	M	M
427	0	4.2	5.22	0.35	-0.18	4.22	M	M
428	0	4.2	5.68	-0.08	-0.91	4.2	M	M
429	0	1.4	1.2	0.36	5.16	4	M	C
430	0	1.3	2.5	0.29	-4.88	4.15	M	C
431	0	1	5.24	1.09	-2.31	4.14	M	C
432	1	1	7.2	0.44	4.99	3.88	M	C
433	1	1.1	7.2	0.89	5.79	3.88	M	C
434	1	1	7.2	1.18	5.3	3.88	M	C
435	1	1.2	7.2	1.47	6.52	3.88	M	C
436	0	4.1	6.17	2.7	9.41	0.71	M	C
437	0	2.5	7.2	3.25	4.01	0.87	M	C
438	1	1.3	7.2	2.47	0.36	3.88	M	C
439	1	1	7.2	2.71	0.36	3.88	M	C
440	1	1.3	7.2	2.58	1.04	3.88	M	C
441	1	2.8	7.2	3.11	0.79	3.88	M	C
442	0	2	2.56	1.75	2	1.48	M	C
443	1	1	7.2	2.12	0.67	4.31	M	C
444	1	1.2	7.2	1.47	0.44	3.88	M	C
445	1	1	7.2	2	0.32	3.88	M	C
446	1	1.7	7.2	1.84	0.78	3.88	M	C
447	1	2.5	7.2	1.57	0.54	3.88	M	C
448	0	4.2	1.87	-0.51	-1.33	0.84	M	M
449	0	4.5	1.8	-0.61	-1.29	0.9	M	M
450	0	4.6	1.99	-0.32	-1.2	0.79	M	M
451	0	4.8	2.07	-0.31	-1.19	0.76	M	M
452	0	1.5	2.18	0.12	-0.35	3.88	M	C
453	1	1.3	2.13	0.58	-0.04	3.88	M	M
454	1	1	2.21	0.61	0.2	3.88	M	M
455	1	1	2.29	0.66	0.2	3.88	M	M
456	1	1.2	2.52	0.92	0.51	4.44	M	M
457	1	1.3	2.94	1.02	0.85	4.25	M	M
458	1	1	3.26	0.67	0.68	4.21	M	M
459	0	2.2	1.2	0.76	1.35	4.39	M	C
460	1	2.1	1.2	0.28	1.42	3.88	M	M

461	1	1.7	1.87	0.9	1.35	3.88	M	M
462	1	1.2	2.78	0.98	1.84	3.88	M	M
463	1	1	3.48	1.2	1.41	3.88	M	M
464	1	1.4	4.21	2.04	1.49	3.88	M	M
465	1	1.5	5.13	2.19	1.83	3.88	M	M
466	1	2	7.2	1.82	8.66	3.88	M	C
467	1	1.3	7.2	1.43	7.07	3.88	M	C
468	1	1.3	7.2	2.06	8.56	4.5	M	C
469	1	1	7.2	1.99	8.02	3.88	M	C
470	0	2.5	2.88	0.46	-0.72	4.14	M	C
471	0	2.2	2.38	0.53	-1	4.02	M	C
472	1	1.8	7.2	0.83	1.88	3.88	M	M
473	1	1.5	7.2	0.6	6.35	3.88	M	M
474	1	1.1	7.2	0.76	-3.51	3.88	M	M
475	1	1	7.2	0.68	1.8	3.88	M	M
476	0	2.1	1.34	1.08	-0.19	0.92	M	M
477	1	1.2	3.5	1.84	2.16	3.88	M	M
478	1	1.2	4.33	2.04	1.78	3.88	M	M
479	1	1.4	5.23	1.28	1.8	3.88	M	M
480	1	1.3	5.55	1.82	0.66	3.88	M	M
481	0	2.8	6.52	1.07	-2.97	0.7	M	C
482	1	2.4	7.2	0.78	6.85	3.42	M	C
483	1	1.7	7.2	1.46	8	3.46	M	C
484	1	1	7.2	1.46	7.64	3.57	M	C
485	1	1	7.2	2.01	8.54	3.61	M	C
486	1	1	7.2	1.77	7.94	3.58	M	C
487	1	1.6	7.2	1.44	7.72	3.62	M	C
488	0	2.4	1.66	-0.1	1.17	1.12	M	C
489	1	2.4	2.47	-0.06	1.63	1.22	M	M
490	1	2.2	3.19	0.36	1.47	1.51	M	M
491	1	2.2	3.91	0.08	1.42	1.55	M	M
492	1	2	4.63	0.28	1.44	1.37	M	M
493	0	2.5	1.33	0.37	0.7	0.71	M	M
494	1	2.2	1.2	0.49	1	1.72	M	M
495	1	1.8	1.61	1.01	1.64	1.73	M	M
496	1	1.4	2.23	0.67	1.3	1.85	M	M
497	0	1.5	2.27	0.48	1.62	3.6	M	C
498	0	1.2	2.94	0.6	1.35	3.42	M	C
499	1	1	3.9	1.34	2.01	3.88	M	M
500	1	1.2	5.07	1.6	2.4	3.88	M	M
501	1	1	5.98	1.39	1.82	3.88	M	M
502	1	1.5	6.94	1.28	1.96	3.88	M	M
503	0	3.1	3.25	1.61	0.47	0.75	M	C

504	1	2.4	3.17	1.51	-0.05	3.22	M	C
505	1	1.8	3.11	1.36	0.1	3.24	M	C
506	0	1.6	2.9	0.41	0.72	0.97	M	M
507	1	1.4	3.16	0.41	0.56	1.76	M	M
508	1	1	3.68	1.2	1.09	1.82	M	M
509	1	1	4.02	0.82	0.69	1.7	M	M
510	1	1.1	4.86	1.2	1.69	1.92	M	M
511	0	1.4	7.2	0.87	8.92	1.85	M	C
512	1	1	7.2	0.87	9.49	1.97	M	C
513	1	1	7.2	0.97	9.22	1.86	M	C
514	1	1.1	7.2	1.19	10.15	1.91	M	C
515	1	1	7.2	0.97	8.48	1.96	M	C
516	0	1.9	1.2	0.63	-0.84	1.46	M	M
517	1	1.4	2.73	1.04	-0.91	3.88	M	M
518	1	1	2.16	1.16	-1.14	3.88	M	M
519	1	1.2	1.8	1.86	-0.7	3.88	M	M
520	0	3.1	1.2	1.33	1.16	0.71	M	C
521	0	2.4	1.2	1.45	1.21	0.71	M	C
522	0	1.8	1.42	1.12	1.04	0.71	M	C
523	1	1	1.4	1.68	1.97	1.19	M	M
524	1	1.4	2.03	1.22	1.25	1.02	M	M
525	1	1.3	2.78	1.39	1.51	1.07	M	M
526	1	1	3.13	0.62	0.72	1.19	M	M
527	0	2.6	1.2	1.37	1.29	0.71	M	C
528	0	2	1.26	1.17	1.3	0.71	M	C
529	0	1.3	1.98	1.4	1.44	0.71	M	C
530	1	1	7.2	1.27	7.31	3.88	M	M
531	1	1.1	7.2	1.49	8.25	3.88	M	M
532	0	1.2	1.2	0.28	-1.64	3.88	M	M
533	1	1.2	1.2	0.04	-1.7	3.88	M	M
534	1	1	1.2	0.72	-1.37	3.88	M	M
535	1	1	1.55	0.05	-1.77	3.88	M	M

Te_{n-1}, Te_m: *types of front vehicle and laterally-following vehicles (motorcycle or passenger cars)*
M: Motorcycle; C: passenger car

APPENDIX H

LIST OF PUBLICATIONS

This thesis is based on the following papers, which have been published and accepted for publication. These papers are appended at the end of the thesis.

Paper 1: has been published in Transport – The institution of Civil Engineers

Phan, L. V., Evdorides, H., Bradford, J., and Mumford, J., (2016). Motorcycle crash risk models for urban roads. Proceedings of the Institution of Civil Engineers, ICE Publishing, DOI: 10.1680/jtran.15.00075.

(This paper is available at: http://www.icevirtuallibrary.com/toc/jtran/0/0)

Paper 2: has been accepted for publication in the 2016 Australasian road safety conference proceedings.

Phan, L. V., Evdorides, H., Lawson, S., Bradford, J., (2016). Crash risk models for a motorcycle-dominated traffic environment. In proceedings of the 2016 Australasian road safety conference, 6-8 September, Canberra, Australia.

(This paper is available at: http://acrs.org.au/publications/acrs-conference-papers/acrs-database/)